Commercial Exploitation and the Origin of Residual Oil Zones: Developing a Case History in the Permian Basin of New Mexico and West Texas

RPSEA PROJECT NUMBER.FINAL

Commercial Exploitation and the Origin of Residual Oil Zones: Developing a Case History in the Permian Basin of New Mexico and West Texas

Contract 81.089 08123-19-RPSEA

June 28, 2012

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Abstract

Commercial Exploitation and the Origin of Residual Oil Zones: Developing a Case History in the Permian Basin of New Mexico and West Texas

A large new resource of recoverable oil has been identified in the San Andres dolomite Formation. Residual Oil Zones, ROZs, up to 300' thick containing 20-40% oil in pores of the dolomitic reservoir are present both below and between presently productive fields. The oil in the ROZs is residual, i.e., not recoverable by primary production methods or water flooding, but oil is recoverable using enhanced oil recovery (EOR) methods such as CO_2 EOR. Although preliminary at this stage, the estimated oil in place in the ROZ's likely exceeds 100 million of barrels of oil and equal to the original oil in place in the zones with mobile oil present (main pay zones, MPZs).

This report identifies and spatially maps the ROZ trend in what is referred to as the Artesia trend of the San Andres formation of Permian, Guadalupian Age. The probable origin of this ROZ is identified, and ways are outlined to explore and identify similar additional ROZ trends in the Basin. The study shows the identification of an ROZ is not necessarily expensive, can be undertaken by small operators, and can add value to both mineral leases and mineral ownership.

ROZs have as their analog, oil fields that possess mobile oil (main pay zones or MPZs), originally flowed oil naturally and then were secondarily water flooded until oil production neared zero. The "waterflooded (swept) intervals" still have 20-40% residual oil in the pore space. The swept zones can be revived using CO_2 EOR. In fact, the Permian Basin (PB) now produces about 200,000 barrels of oil per from CO_2 floods. On average, an additional recovery of 10-20% of the original oil in place in a field is possible using CO_2. This is oil that would not be recoverable without the aid of an injectant that liberates the oil.

What the industry has learned is that there is not a lot of difference between a MPZ interval that has been waterflooded and a ROZ. This study helps confirm that the ROZs have been flooded by Mother Nature, due to tectonic changes that have occurred after the establishment of a very large ancestral oil trap. The movable oil was swept away by a natural waterflood leaving behind the ROZs, hence the name, mother nature's water flood. Eleven CO_2 EOR projects are now underway proving that the naturally waterflooded intervals are commercially attractive as are those on man's waterfloods.

ROZs are evidenced during drilling by "shows" of oil in mud, in cuttings and cores, and by log calculations showing residual oil saturations. Because of the shows, well completions or drill stem tests have often been attempted but result in recoveries of black sulfur water, leading to expensive dry holes.

To define the Artesia Trend well logs, formation tops, drill stem tests, core data, water composition and pressure analysis, and geological data were gathered in an attempt to define and model the hydrological sweep process. Pressures recorded in drill tests were particularly useful in defining piezometric conditions. Careful definition and modeling of present ground water movement, and analysis of the groundwater conditions prior to major water extraction allowed calculation of rock properties that in a model reliably calculated movement of water in passed geologic time. The model over geologic time concludes that the water charge entered the San Andres in the region west of Artesia,

NM starting after the uplift in the Miocene Period and began its slow migration within the San Andres formation “fairways” to an area northeast of Fort Stockton coincident with the sulfur deposits there. During the migration of the water it displaced oil that was part of the paleo-trap causing sweep (displacement) of the oil and leaving the ROZs. The construct of the hydrological model allows scoping of the sweep process and insights as to the hydrodynamics and regional hydrology.

Evidence exists of other trends of ROZs in the Permian Basin. Using the methods found effective in this study new investigations are being conducted to define their origins and map their distributions. The work should allow a more robust determination of the magnitude of the technically recoverable oil resource due to EOR in the Permian Basin.

Principle Investigator: Robert Trentham

Signature:

Date: 6/28/2012

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Project Acknowledgements

We would like to recognize the vital participants in our project and their areas of expertise. Without their energy, efforts and diligence, our project would not have been successful:

L. Steven Melzer, Melzer Consulting, Midland - All phases of the project.

Phil Eager, Consultant, Midland – Sulfur Deposits, Data Gathering, verification and reconciliation.

Arcadis U. S. for the Groundwater Modeling Effort,
In the Midland Office
David Vance, Kuohui Suchecki, Steve Tischer
On the Remote Modeling Team
Gaston Leone, Scott Niekamp, and Michael Kladias

Martin Cassidy, University of Houston – Oil Geochemistry,

Jimmy Hawkins, Roosevelt Resources - Log analysis

Robert Kiker, Consultant – Production Data, Technology Transfer

William LeMay, Consultant – Historical Field and ROZ information

Hoxie Smith, Director PPDC Midland College – Logistic Support

Stephen Robichaud, Consultant, Midland – Drill Stem Test interpretation

Legado Resources and all their office & field staff – Matching Funds and ROZ flooding information

Chevron Corp - Matching funds and Some key Field Data

Executive Summary

It is now realized that residual oil zones, ROZs, contain oil that is recoverable by the use of miscible CO_2 enhanced oil recovery (EOR). Of the 15% to 35% oil trapped in ROZs some 10% to 20% can be recovered by CO_2 flooding. The CO_2 enters the oil causing it to swell, become less viscous and be forced out of pores. It may also change the surface tension of the oil and its attaction to the rock. Some of the oil is forced from the pores and the CO_2 is trapped, becomming sequestered. The idea that one can sequester CO_2 during EOR has lead some to a name change of the title Carbon Capture and Storage CCS, to Carbon Capture Use and Storage CCUS.

For a long period of time, the oil in place in reservoirs beneath the oil/water contacts was professed to be due to capillary "smearing" and surface tension in rock/water and oil phases. The widely accepted terminology was transition zones. The language and lab tests supporting the concept effectively excluded the possibility that thick intervals of residual oil could be explained in other ways and that, in fact, the science of capillary forces could be superimposed on a more fundamental theory for why thick zones of residual oil (ROZs) exist.

The concept of post-entrapment tectonic adjustments to oil bearing basins was beginning to brought to more widespread attention in 2006 wherein three mechanisms for readjustments of paleo entrapments was proposed (Melzer, 2006). One of these types, lateral flushing from a nearby uplift, was seen to be especially dominant in the Permian Basin region of West Texas and southeastern New Mexico. In the meantime, several enhanced oil recovery projects were privately demonstrating economic oil recovery from the residual oil zones (ROZs) elevating the importance of understanding their origins and distribution.

It was recognized that, if the lateral flushing mechanics was a plausible explanation for the ROZs, such a process might be modeled in a hydrological sense to attempt to better understand the process, characterize the reservoirs, and explain the nature of the economic potential of the intervals. This study was designed as an attempt to model a specific fairway of flushing rimming the Delaware Basin portion of the greater Permian Basin and would require an extensive data collection effort from historical wells and studies in an attempt to characterize both the input rock properties and fluid characteristics.

The investigation of ROZs requires a multidisciplinary team. The science of lateral oil flushing has components of geochemistry, biochemistry, reservoir engineering, and geology including tectonic stage reconstruction. This team gathered data from the selected San Andres formation fairway of interest and consisted of well logs, formation tops, drill stem tests, core data, geological and hydrological studies. Essential data also came from earlier studies having to do with Capitan Reef hydrology, professional association compendia and their oil field studies, and regulatory agency required oil and gas data reporting.

The results of the data collection formed the basis for a hydrological model simulation wherein modern hydrological conditions were used to calibrate the model in order to project back in geological time to the predominate period of entrapment flushing. The results of the model work would be subject to a large number of assumptions but could be constrained by the observations of tilted oil water contacts, sulfur occurrences, water salinities, and other anecdotal data that, taken in aggregate, provides confidence of the model and flushing process.

Results of the study confirmed the presence of thick and extensive greenfield ROZs, i.e., where no main pay zones are present. The hydrodynamic modeling demonstrated that the mechanics of flushing are measured in units of tens to hundreds of feet (movement) of water per 1000 years. This agreed with independent, analytical calculations of piezometric head effects on oi/water contact tilts and attempts to model the process using modern first-principle physics and simulators (Koperna and Kuuskraa, 2006).

The Artesia fairway was found to extend from Northwest Shelf of New Mexico east to the Central Basin Platform and then south along the West side of the platform to Pecos county. The lateral limits of the fairway on the west side of the Central Basin Platform were defined as the San Andres shelf to basin transition on the basin side, and on the east platform side transition from the intertidal carbonate dominated faces to the evaporite dominated sabkhas facies tract.

In addition to horizontally dividing the trend based on facies and permeabilities, the trend was divided vertically into a number of different, stratigraphically distinct, intervals within the San Andres. The middle – upper San Andres "Judkins" interval has been identified as the "flow path". Careful investigation of present Hydrologic regime and of the hydrologic regime before the withdrawal of water for agriculture and water flooding of oil fields has allowed calculation of rock and water properties to put into models of water flow in past geologic time. The model calculates tilt in oil water contacts as exist in a number of fields. It is determined thqt between 46 and 17.3 pore volumes of water have passed through the Artesia trend!

Identification of the Artesia fairway favorable for individual ROZ deposits should allow explorationists to focus exploratory efforts to find them. Dissemination of information about ROZs through lectures and symposiums both locally and country wide has lead to new CO_2 EOR projects targeting just ROZs in addition to adding stratigraphic sections of ROZs to the CO_2 floods already underway in old producing fields of the Permian basin.

Study of Roz's in other basins by other groups has begun The fact that significant CO_2 is trapped in an ROZ as the oil is produced has encouraged groups studying Carbon Capture and Sequestration, CCS, to move to Carbon Capture Use and Sequestration, CCUS.

With the success of this study delineation of other ROZ trends in the Permian Basin is already under way.

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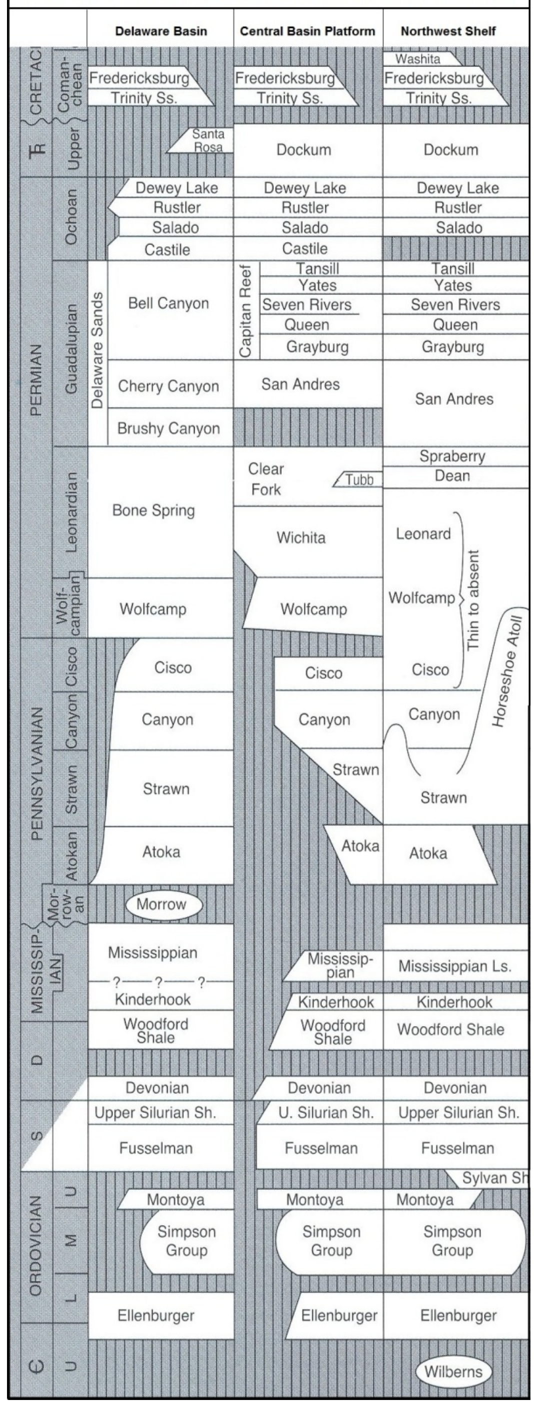
1.0 INTRODUCTION AND PROJECT TEAM BUILDING

As the economic recovery of oil from below the oil/water contact began showing signs of commercial excitement in the Permian Basin, it became obvious that a more complete understanding of the science of the origins of the intervals was needed. The oil industry had considered capillary forces and surface interfacial tension between the rock and the oil and water were the controlling parameters. Background work performed in the Permian Basin in the 1990's by Lindsay, 1998 and Brown, 2001 had pointed the way to a lateral flushing concept. Melzer (2006) reframed and generalized the idea to "mother nature's" water flooding and presented two other models (besides the lateral flushing) for creation of residual oil zones (ROZs). In the Permian Basin, however, the evidence was clearly in the camp that the lateral flushing of paleo oil traps was the leading hypothesis to explain the thick and pervasive occurrence of residual oil zones.

FIG. 1.1 PERMIAN BASIN STRATIGRAPHIC SECTIONS



In the time frame between 2001 and 2009, some private, commercially-driven work illustrated how widespread the Type 3 ROZs (Altered Hydrodynamic Flow Fields) were and it became clear that a step-by-step development of a more regional research plan was needed. The possibility of hydrologically simulating the lateral flushing of paleo traps was postulated as a useful approach but would require selection of an area to model, assembling a multidisciplinary team to gather the needed rock and fluid data, set up the hydrodynamic model, and perform the simulation. The private work suggested that the San Andres formation (Fig. 1.1) was of paramount commercial interest because of the thick intervals of reservoir quality rock, the large CO_2 EOR data base, and the seemingly ubiquitous nature of residual oil within the formation. Unfortunately, the selection of a flushing fairway was complicated by the existence of commercial interests that had staked out certain prime areas for rights acquisition. Those interests required excluding several candidate areas and the study was forced to move to a fairway where commercial interests were not yet in play. As a result, the project selected the shelf carbonate trend rimming the Delaware Basin of southeastern New Mexico and West Texas. The selected fairway was low on commercial priority lists due to a general lack of subsurface knowledge owed in part to the lack of main pay zones within the fairway trend.

The plan of research required a thorough literature review of what was known about the Guadalupian shelf carbonates rimming that part of the Permian Basin and a quick scoping effort to look for the useable well penetrations.

Conducting studies in a mature oil environment like the Permian Basin almost assures access to a large number of existing wells with data to assist in the characterization and modeling tasks. The disadvantage is that sorting through the mass of data to collect the important model inputs and attribute decisions requires broad based experience to make a manageable task out of the time intensive effort.

Since the effort was, in many ways, the first of a kind, it was expected that many lessons would be learned along the way. Careful selection of participants and monthly meetings of the data gathering and modeling team would likely yield benefits difficult to imagine in the early stages of research planning.

In the pre-proposal stage of project formulation, the role of sulfur in the lateral flushing process was identified as an important feature in the Permian Basin ROZ process. Mr. Phil Eager was experienced with the sulfur exploration industry and brought considerable talent and experience relating to science and distribution of sulfur deposits in both the Permian Basin and elsewhere. But the role of sulfur would require expertise in geochemistry and Mr. David Vance of Arcadis was recruited to aid in providing the needed insights in the chemical reactions. Somewhat fortuitously, he also brought knowledge of the role played by anaerobic bacteria, especially sulfate reducing microbes. Their importance, as it turns out, would prove of infinite value in not only the project modeling but also in the possibility of rock alteration that can occur during the lateral flushing process. Mr. Vance and Steve Tischer, also of Arcadis, would be critical in providing research ideas as well as in guiding the modeling team throughout the study.

Through Mr. Melzer's connections and the CO_2 Flooding Conference, Dr, Martin Cassidy of the University of Houston joined the team very early on and also brought invaluable geochemistry expertise to the study. His intimate knowledge of organic and isotopic chemistry led the team to seeking explanations of some of the variability in the sulfur waters and organic chemicals resulting from the sulfate reduction processes active in the ROZs.

The team had a tremendous head start in identifying the generalized outline of the fairway through the experience and expertise that Dr. Robert Trentham possesses. His experience during his years at Chevron and, later on, in private consulting practice, led the project to the selected area and allowed a general delineation of the chosen (Artesia) San Andres formation fairway. .His guidance through the data acquisition and model parameter selection phase was also invaluable.

Ms. Kuohui Suchecki and Phil Eager led the very detailed data acquisition effort with the help of Ms. Saswati Chakraborty. During the course of study, Steve Robicheau was recruited to assist with identifying, screening and analyzing the drill stem test data to provide more appropriate rock system permeability values for the modeling effort.

Mr. Bill Lemay, former consulting geologist in Roswell and a past Director of the New Mexico Oil Conservation District was invaluable regarding the New Mexico portion of the Artesia

Fairway. Some of his early publications actually recognized what we now term as the “fairway” and also helped immensely with advice in avoiding some blind alleys regarding data collection. Mr. Robert Kiker, retired engineer from Conoco and president of the Applied Petroleum Technology Academy, also aided in the latter task as well as providing his considerable experience in the technology transfer activities.

The value of having corporate involvement through industry partners not only helped stimulate the project from a technical perspective but also helped to keep the projects serving commercial goals. Too often, research projects end up focusing on justifying more research wherein one project is intended to set up the next research project regardless of whether the results impact the commercial community in any way. Our industry partners, Chevron and Legado, clearly helped keep the project directed on a pathway to the understanding of ROZs in such a way that it would lead to more efficient and larger commercial oil exploitation opportunities. The personnel at both organizations assisted with advice and assistance whenever approached. They also provided a sounding board for some of the wilder ideas that required vetting prior to presentation to a larger audience.

The Arcadis modeling team, led by Mssrs. Scott Niekamp and Gaston Leone and ably assisted by Ms. Kuohui Suchecki were faced with the unenviable task of characterizing not only the modern fairway hydrodynamics but also the Tertiary aged flushing mechanics that would be so important to the sweeping of the paleo traps and formation of the ROZs. Their work required a geologic reconstruction to a level and purpose that had never been accomplished before. They leaned heavily on the entire team, especially Dr. Trentham, and some key references that are repeatedly cited in Sections 7 and 8. The work product reflects many long hours of discussion and debate over key points that form the basis of the model results.

It is one thing to successfully accomplish an important research project but it is quite another to perform successful outreach to the technical community to allow the work to have a broad impact. A considerable effort was undertaken during the entire project term by Dr. Trentham and Mr. Melzer, ably assisted by Mr, Kiker to assure that the on-going work was widely disseminated. Mr. Melzer’s connections to the engineering communities within both the governmental and industrial organizations proved important while Dr. Trentham’s connections to the geological community, both within and outside the Permian Basin were invaluable. It also helped to have a subject that was receiving growing recognition throughout the enhanced oil recovery and sequestration communities. The technology transfer activities began with a ROZ Symposium in Midland that was very well attended, brought a new perspective to the subject of residual oil zones, and proved to be an excellent learning experience for both the audience and the research team. Over 50 separate events followed the initial outreach effort with attention given to local, statewide and national audiences. The model results were not available until the end of the study but the ROZ science, supported by the data collection effort, was sufficiently novel that the interest in the study grew to such a level that many of the events were unsolicited by the ROZ team. A full list of the technology transfer events for the project is provided in Appendix A-1.

2.0. THE SCIENCE OF RESIDUAL OIL ZONES

For more than 100 years, the U.S. oil industry has made an impressive series of technological advances in finding, describing and producing modern oil and gas entrapments. During the last half of that time, the technology of waterflooding was mastered while enhanced recovery (tertiary) techniques came along later. The enhanced oil recovery (EOR) technologies were designed to take advantage of all the oil that was bypassed in the waterflood stage because water and oil did not mix. The application of EOR technologies recognized that the properties of the oil needed to be altered to be producible. In the very recent past, what has become understood is that man's waterfloods might not make the only targets for EOR. In basins where multiple stages of tectonics are present, ancient or "paleo" oil traps could have been naturally waterflooded and become candidates for EOR as well. Recent work in the Permian Basin (Melzer, 2006 and Biagiotti, 2009) has shown that those zones, herein called residual oil zones (ROZs), are economic and further, that they are large in size and owe their existence to one, or a combination, of three mechanisms.

The ROZ science is based upon the observation that oil can episodically migrate in the subsurface. The displaced oil can move from an interim trap before it finally finds its way to 1) the surface, 2) near surface in the form of oil (tar) sands, or 3) another entrapment 'home' in a modern trap. What sets up the episodic movement are successive stages of tectonics.

Many of the world's oil basins can be shown to have had more than one stage of tectonic history. In other words, the original deposition of the rocks, geologic subsidence (deep burial), generation of the oil and migration to a trap in the subsurface can be simplified and referred to as the first stage of tectonics and another stage can occur later on wherein the basin gets tilted, faulted or mountains form alongside or within the ancestral basin. Detailed discussion of these ROZ types is presented in Melzer, 2006 and also later herein.

To cite specific examples, the ancestral Big Horn and Williston Basins had pre-established oil migration and paleo oil entrapments. Those Paleozoic basins were sufficiently deep that oil and gas were generated and migrated to first stage entrapments. Traps were then altered by the Laramide tectonics (Big Horn Mountains and Black Hills Uplift). Massive amounts of oil were moved around (Enhanced Oil Recovery Institute, 2012). Without question, much of it was lost to the surface or new traps but much was also left behind in the form of residual oil. Such was also the case for the ancestral Permian Basin, also altered by a Laramide stage of tectonics and then further altered by a later stage of tectonics, the Basin and Range extensional orogeny. Structural geologists have attempted to reconstruct the historical development of these basins. One notable example of such a reconstruction is illustrated in cross sections of three Permian Basin stages as shown in Figures 2.2, 2.3 and 2.4 (Lindsay, 2001).

Although the late stages of tectonics can cause water to invade and displace the mobile oil from the ancestral traps, what the industry is learning today, is that process was not perfectly efficient, just like the industry is not perfect when it waterfloods a modern oil reservoir. The paleo waterfloods left behind oil saturations (S_{orw} – i.e., residual oil saturation to waterflooding) that can be very similar to the S_{orw} of a modern waterflood. Those naturally flooded intervals can be flooded with enhanced oil recovery methods such as CO_2 EOR, chemical methods, or other EOR techniques. As mentioned, these techniques allow production of that oil by changing its properties, reducing its tendency to stick to the rock, and/or making it less viscous and able to flow more easily in the reservoir.

During the latter half of the last century, industry demonstrated that commercial EOR projects can follow waterfloods. Over 120 CO_2 EOR projects are active today. EOR in naturally waterflooded intervals has just begun but, it can be said today, that economically producing naturally waterflooded zones is beyond a theory now. Eleven of these projects are now underway in the Permian Basin (Figure 2.1) and, at the time of this report, are making in excess of 11,000 barrels of oil per day.

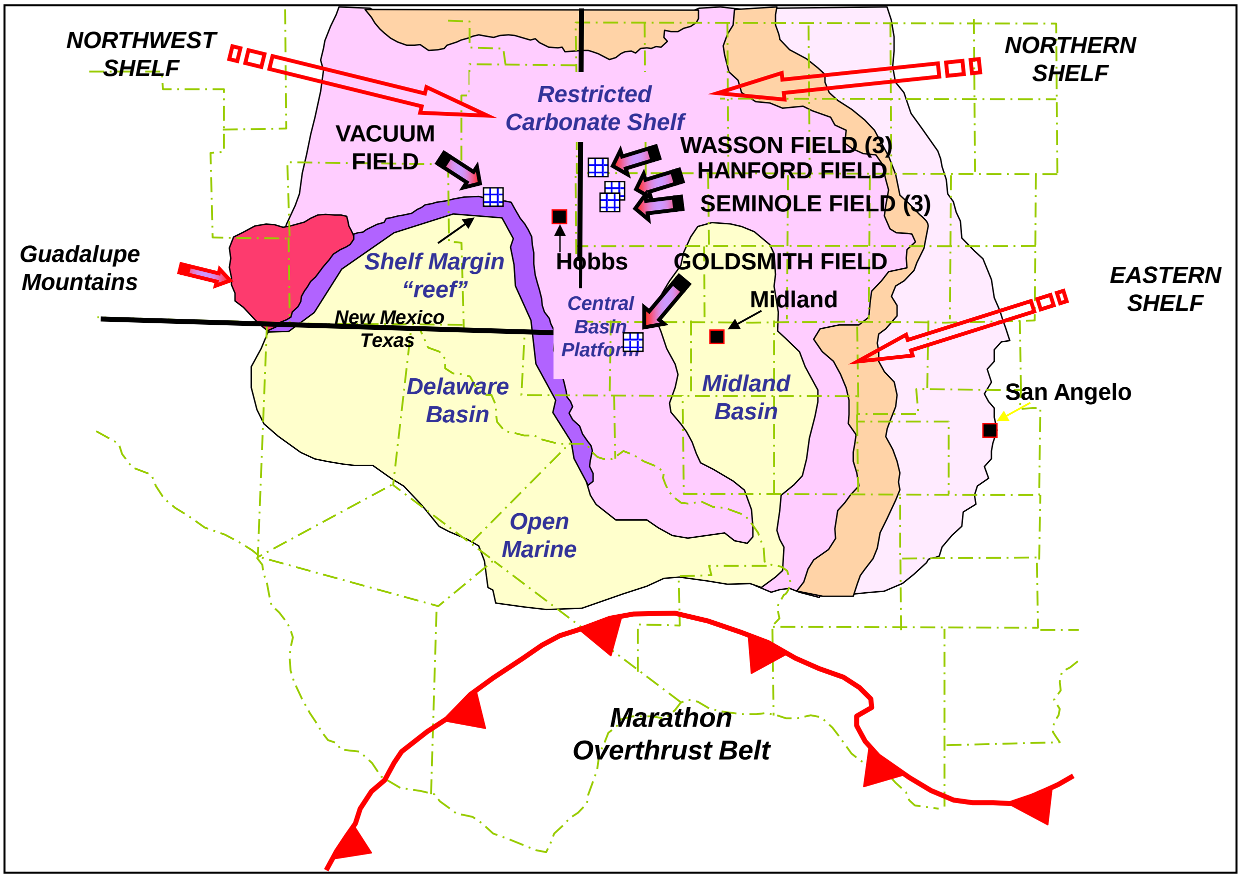


Figure 2.1 - Middle San Andres Paleogeography Illustrating the Locations of ROZ Projects

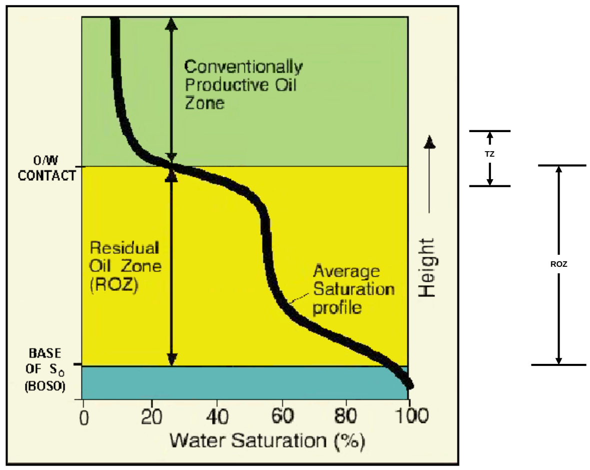
The oil and gas industry has been somewhat slow in recognizing that large EOR targets exist in the subsurface. Much of the reason for this has been the forceful application of capillary science and oil saturation "smearing" to explain these zones. As was discussed in the introduction, the term transition zone is commonly used and implies a cross-sectional profile that uniformly grades from the S_o of the oil column, say 75-90% as was is commonly observed in the West Texas fields, to a value of zero.

However, the industry today is recognizing that the use of transition zone terminology is too restrictive, most have moved to adopting the more inclusive term - residual oil zone. The need may now be obvious to the reader as this terminology can, by definition, include the previously discussed vertical or horizontal water induced displacement of oil and, therefore, be inclusive to naturally waterflooded intervals in the subsurface. ROZs will thereby be inclusive of intervals below conventional oil fields as well as intervals than may not have a modern main pay zone (wherein all of the previously trapped and mobile oil phase was displaced by natural processes).

Where the historical and modern terminology clash most frequently is in those situations where both main pay zones (MPZs) and ROZs exist. Capillary smearing of oil and water saturations is, indeed, a real process and the commonly modeled methods create gradationally alternating oil saturations. And, as most commonly used, the transition zone interval includes as upper depth interval that produces oil with a commercial oil percentage – commonly called "cut".

Some field completion strategies may or may not have included that interval in original completion of wells for primary production. In contrast, and as used herein, the term residual oil zone would include all but the upper portion of that upper transition zone profile and therefore consist of the interval wherein a commercial primary and secondary production phase was not present. Another significant point to make is that it would also include the zones like that shown in the Seminole San Andres Unit (SSAU) oil saturation profile of Figure 2.2 where the gradational nature is interrupted by a middle region of relatively constant S_o.

Figure 2.2: Seminole Field Water Saturation Profile*



* Adapted from Brown, A. (1991)

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To further emphasize, the reason that the term ROZ is preferred herein is to differentiate those situations that exist for reasons beyond normal capillary and interfacial tensional effects. For example, if the original oil entrapment possessed a thicker oil column in its geologic past and a lower portion was invaded by water, the displaced interval would leave an oil saturation much like that attributed to the remaining oil saturation in a swept zone in a secondary waterflood, S_{ow}. Such is certainly the case at the SSAU, Figure 2.2. These types of reservoirs can possess anomalously thick residual oil zones, can exist where no main pay zones (MPZ)s are present, and contribute substantial additional EOR reserves above and beyond those attributed to the MPZ's. In fact, if one includes the SSAU ROZ oil in place numbers with the original oil in place attributed to the MPZ (1 billion barrels) the numbers effectively double to 2 billion barrels.

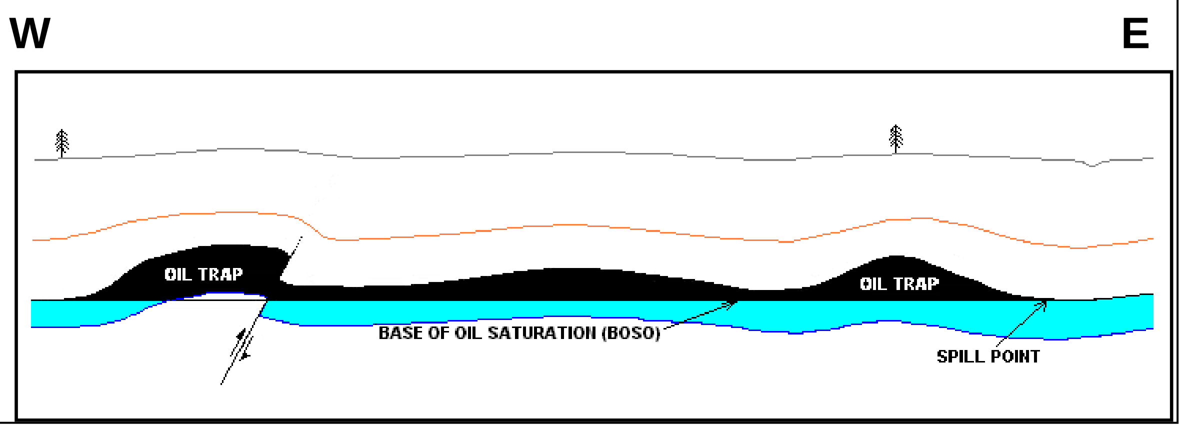
One might conclude that transition zone thinking and terminology would necessitate thin zones below the oil/water contacts. Thus, this model could lead to leaving out the opportunity for significant oil resources below modern entrapments. Additionally, one would necessarily exclude any EOR resources where no mobile oil (modern day) fields were present. Mounting evidence is accumulating suggesting that there are very large regions of residual oil without overlying main pay zones and, further, that these may exist in a large number of worldwide basins. With the changing forces that can move oil around after original paleo emplacement, it would be expected that such opportunities for residual oil zones could be common. When this is placed in context with the emergent technical and economic success of CO_2 flooding ROZs in the Permian Basin, it creates an urgent need to 1) fully categorize the important causes of residual oil zones, 2) examine and reconstruct the evidence of such tectonic forces at work, and 3) broadly examine and characterize the opportunities for EOR within these residual oil zones. This report describes a small but important first step of that process.

2.1 ROZ Zone Types

The remainder of this section of the report is dedicated to a very brief description of the science of origins of residual oil zones. As already discussed, another early version and more complete treatment of the subject was presented in Melzer, 2006.

It will provide instructive to present a hypothetical trap that might be present at the end of subsidence, oil generation and migration. Let us call that the first stage of tectonics in an oil basin. Figure 2.3 illustrates that hypothetical, original oil entrapment with a hydrocarbon spill point on the east.

Figure 2.3: Original Oil Accumulation Under Static Aquifer Conditions (A Hypothetical Example)



Basin Tilt **(Type 1 ROZ).** The entrapment is subsequently subjected to a regional westward basinal tilt (Figure 2.4a). This imaginary situation preserves the identical spill point for the original hydrocarbon accumulation and illustrates that the oil column has been thinned on the west side leaving behind a zone of "water swept" oil. The base of oil saturation, wherein S_o is zero, has also been tilted therefore a measure of the degree of tilt that has occurred. The oil-water contact (of movable oil) is controlled by gravity alone and is horizontal. The resulting ROZ is wedge shaped with the downdip side being thicker.

The swept interval is somewhat analogous to oil produced in a natural water drive reservoir wherein the invaded zone is left with a residual oil saturation to water (S_{orw}) and equally analogous to the swept zones in a pattern waterflood. The relative displacement curves for oil and water are the tools by which the industry estimates the displaced oil in these situations. The remaining (or residual) oil left behind is the target oil which can be produced via CO_2 flooding or other EOR methods.

Breached and Reformed Reservoir Seals **(Type 2 ROZ)**. Figure 2.3b presents a second source of residual oil zones. Here, the original oil entrapment has been breached. This can occur, for example, by buildup of fluid pressures during the formative reservoir stage, escape of a portion of all of the hydrocarbons, subsequent healing of the seal, and re-entrapment of hydrocarbons. If the second entrapment contains a thinner oil column than was originally present, a residual oil zone would be present. Proving the transient loss of seal integrity would be difficult of course, but many cases exist in the field that point toward this type of ROZ.

In this case, both the base of oil saturation that was controlled by the bottom of the transition zone in the original entrapment, and the oil-water contacts, controlled by base of the undisplaced or re-accumulated mobile oil phase, are horizontal. Gas-oil ratios of these reservoirs are often anomalously low due to the weaker seal capacity. Tar mats and other solid hydrocarbons present within the oil column are observed on occasion.

Altered Hydrodynamic Flow Fields **(Type 3 ROZ).** The general lack of commercial interest in deep oil basin aquifers has generated little research, at least as is evidenced by only scattered

Figure 2.4a: Original Accumulation Subject to a Westward Regional Tilt & Forming a ROZ

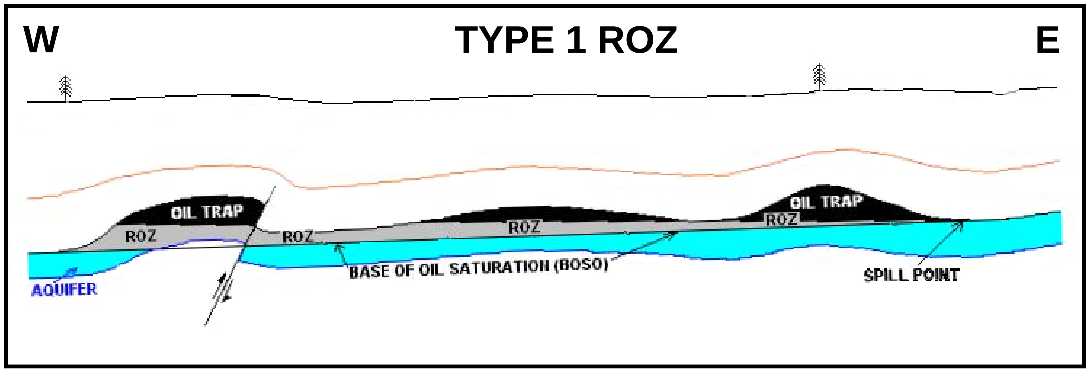


Figure 2.4b: Original Accumulation with a Breached then Repaired Seal & Forming a ROZ

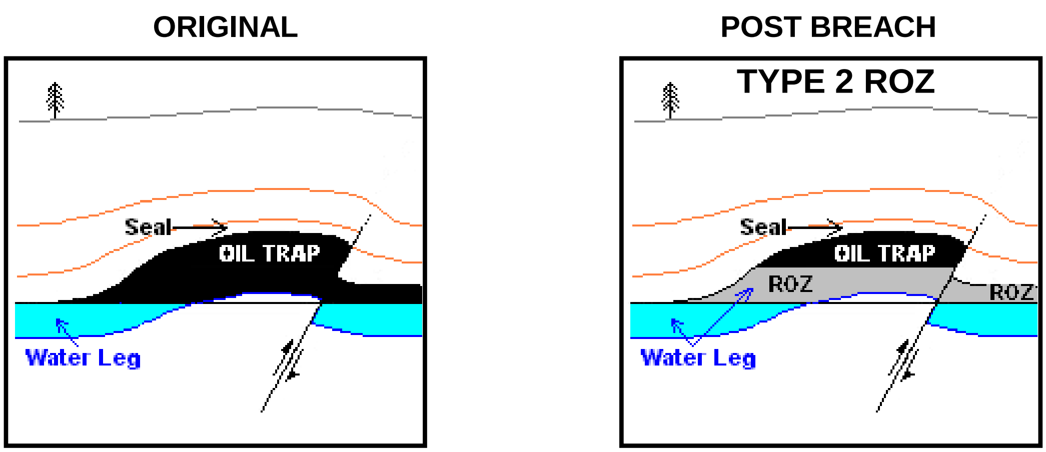
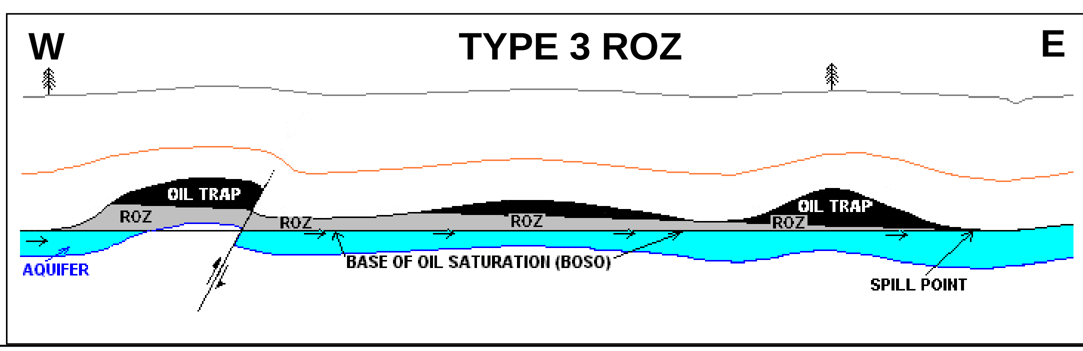


Figure 2.4c: Change in Hydrodynamic Conditions, Sweep of the Lower Oil Column, Oil/water Contact Tilt, and Development Of The Residual Oil Zone



references in the petroleum geology literature. However, one notable exception to that lack of interest is the collection of studies devoted to understanding hydrodynamically trapped hydrocarbons (examples of which are Brown (2001), Berg et al, (1994), and Hubbert, M.K. (1953)). In this body of work, the understanding of currently active aquifer flow-fields can lead to finding and describing accumulations that are not explained by normal subsurface structural closure or stratigraphic confinement theories. Hubbert (1953) provides a particularly insightful discussion of what has been called hydrodynamic traps and the reader is referred to this work for detailed discussions of not only oil but also gas traps subject to hydrodynamic forces.

The above body of geologic work is devoted to exploration objectives or, as alternatively stated, is concerned with where the hydrocarbons migrate when subject to hydrodynamic flow. The interest herein, however, is effectively the reverse: i.e., from where did the hydrocarbons migrate. Almost no reference work was found to assist in this endeavor. Fortunately, those three notable exceptions above all indirectly relate to this third class of residual oil zone origin, altered hydrodynamic flow fields.

Figure 2.4c shows the same original entrapment seen earlier but uses an example west-to-east hydrodynamic flow-field to explain the tilted oil-water contact. This type of ROZ is now understood to be the prevalent type in at least one very important region, the Permian Basin. As a result, it forms the basis for this entire report. The difference between the examples in Figure 2.4 can be seen in that the oil-water contact for Type 3 is not horizontal but is tilted, in this case owed to the hydrodynamic forces on the oil column. Hubbert (1953) provides analytical methods (Equation 1 below) to determine contact tilts based upon the flow-field and densities of the oil and water. Since many oilfields were unitized for reasons of planned water flooding, rigorous calculations of oil-in-place were necessary which would require detailed structural contouring of the oil-water contact. The two ROZ demonstration projects at Wasson and Seminole have OWC structure maps filed for record in Texas Railroad Commission unitization filings ROZ demonstration projects which show this tilted OWC attribute. With that information and knowledge of the oil and water densities, one can calculate the hydrodynamic flow field responsible for the contact tilt beneath the oil leg through the use of the following formula.

Oil-water Contact tilt $= dz/dx = - dp/dx \times (rho_w/(rho_w - rho_o))$……… *Equation 1*

where: dp/dx *= Pressure (Potentiometric) Gradient of the Aquifer*
rho_w *= Density of the Water in the Aquifer*
rho_o *= Density of the Oil*

One should exercise care to avoid assuming that the documented OWC tilt is due to current hydrodynamic gradients. The tilt can be assumed to be the result of the maximum gradient but current gradients may be lower (or even non-existent if fluid withdrawals are significant). Time, varying gradients due to climatic variations, subsequent tectonics, and denudation at sources and outcrops all likely play into the distribution of the oil saturations through the ROZ.

Oil water contact information is often readily available for most fields; determining thicknesses of the ROZ can be more problematic. Very few cases will be found like the Seminole and Wasson fields in West Texas wherein core data was acquired to confidently establish the base of oil saturation (BOSO). In other situations, the BOSO can be approximated by such things as the loss of oil shows within the drill cuttings or sample cuts or by the use of borehole logs if high confidence in water salinities (resistivities) is present. Another technique (called the Hingle Plot) discussed in Brown (2001) that takes advantage of the divergence of the ratio of formation resistivity to density above and below the BOSO. But in this technique, the BOSO is often redefined to be depth at which low oil saturations do not affect formation resisitivities. Since this oil saturation is generally below 20%, the interval is not considered commercially productive even using EOR techniques. Produced water cuts are extremely high throughout the ROZ (>>99%) and, since perforations are typically spread out along thick depth intervals, no confidence is placed in utilization of water cut data for determination of the BOSO.

One final and very important point about the Type 3 ROZ is that it does not necessarily possess a retained oil column as can be observed in a portion of Fig 2.4c. In fact, in some cases, and in much of the modeled area included in this report, the entire original paleo trap is now a ROZ. This situation is especially prevalent where only low relief structure exists over a regional paleo trap and where high hydrodynamic gradients are present. Berg, et al, (1994) alludes to these types of traps being present in the Billings Nose area of western North Dakota Gratton, P.J. F. and LeMay. W.J. (1968) allude to their presence in the San Andres of New Mexico, and recent work by the Enhanced Oil Recovery Institute of the University of Wyoming is reporting them in the Big Horn Basin of northwestern (Mohrbacher, D. et al (2011).

2.2. Permian Basin and the Concept of Fairways

Type 3 ROZs require a source of water for the flushing action, a pathway of movement, and a discharge area. Of course, the pathway of movement will need to be reservoir quality rock whether filled with oil or devoid of hydrocarbons. Where mobile oil was present, the process forms a ROZ and, where structural closure on top of the reservoir could not isolate some primary oil from the flowstream below, the ROZs have been dubbed a "greenfield" (no existing primary productive field) as opposed to a brownfield ROZ which lies beneath a MPZ.

The fairways, as understood now in the Permian Basin San Andres formation, generally trend along the higher energy shelf facies. Since the San Andres represents such a long period of geological time and up to 1400 feet of reservoir thickness, multiple shore facies, vertically separated in space, are often present. The project was designed to gather data on a very major one, stretching from near the uplifted outcrop of the San Andres in New Mexico along the north side of the Delaware Basin and down the west side of the Central Basin Platform. Figure 2.1 hints at the location of this fairway and future sections will further outline the chosen fairway and describe the detailed data gathering effort to characterize the rock properties and lateral flow.

3.0. COMMERCIAL DEMONSTRATIONS OF OIL RECOVERY FROM RESIDUAL OIL ZONES

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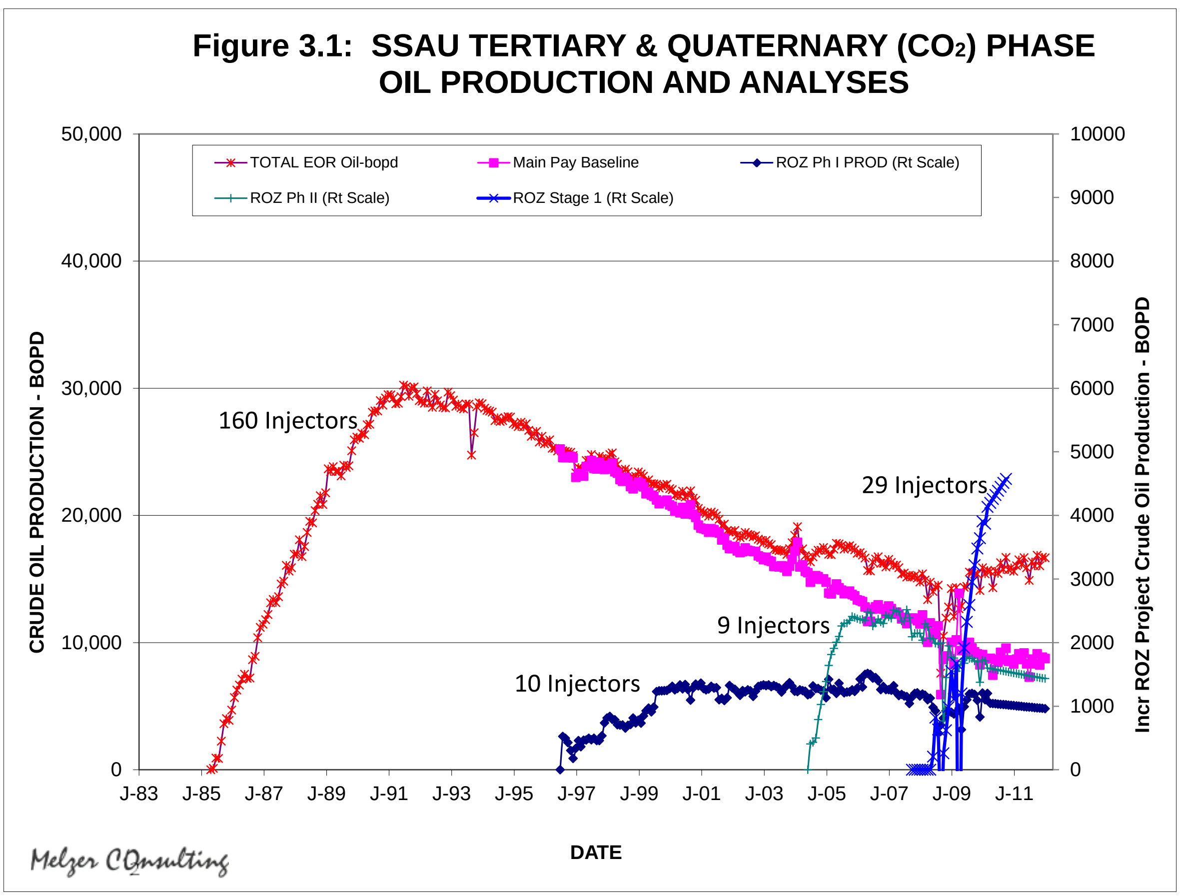
Since, by definition, residual oil zones are at waterflood residual oil saturation (S_{orw}), it is not possible to produce commercial quantities of oil from the intervals in either primary or secondary phases of production. Thus the commercial importance has to be due solely to enhanced oil extraction. And, if the intervals were insignificant in thickness and/or extent, their potential contributions to oil resources would be negligible. What has become very obvious during the course of this subject study is, however, that the ROZ resources are very, very large in an areal sense and of sufficient vertical thickness to potentially contribute billions of barrels of oil reserves to the Permian Basin. Considerable future work will be necessary to spatially map and quantify these resources.

A first order study of the ROZ resource beneath 56 fields has been performed in Koperna and Kuuskraa (2006). Using their described methodology which included the transition zone interval below the oil/water contact just above the ROZ resources, the scoping study determined that over 30 billion barrels of oil were in place.

The Seminole San Andres Unit (SSAU), operated by the Hess Corporation, is the best documented project to illustrate the points of ROZ commerciality. Four separate projects have been implemented there attempting to produce EOR oil. The Phase I pilot project was begun in 1996 and consisted of 10 injection-centered 80-acre patterns. The ROZ interval was added to the MPZ CO_2 flood by deepening both the injector and producer wells and by commingling both injection and production. Figure 3.1 illustrates the oil response of the project as reported



in Biagioitti (2009). One can see that a peak oil response of 1500 bopd was established and an estimated two million barrels of crude oil has been produced to date from the 300' interval of the Phase 1 ROZ project.

In 2001, the operator implemented a second pilot (Phase II), also in the area of the ongoing MPZ flood, wherein an interpretive weakness in the Phase I pilot was corrected by providing dedicated injection to the ROZ interval (9 new injector wells). In addition, new wells were drilled for dedicated ROZ production and the pattern configuration was reduced to 40-acre spacing. Figure 3.1 also illustrates the faster response of the Phase II pilot illustrating, once again, quite significant oil response with a peak ROZ oil production of 1500 bopd.

With the success of the ROZ pilots and consent of the other non-operating partners in the SSAU, Hess implemented Stage 1 of the full-field ROZ program in 2006. Twenty-nine injectors were drilled to dedicate injection in the ROZ interval and existing MPZ producers were deepened for commingled production. The pattern of choice was 80-acres, chosen primarily to minimize new drills but clearly acceptable because of higher injectivities and the faster response time of the ROZ to injection than was observed in the MPZ CO_2 flood. Figure 3.1 provides our interpretation of the response of the entire field to CO_2 EOR in the MPZ program and the three ROZ projects to date. We estimate that the total production from the SSAU ROZ at the time of this report exceeds 5400 bopd and is headed to a higher peak (forecasts suggest a peak of >8000 bopd for the combined three projects). The reader is reminded that this interval would produce no oil in primary or secondary phases of production.

Hess has begun implementation of Stage 2 of the full field ROZ program which is to consist of another 19 injection centered patterns and is scheduled for operational completion by the end of 2012. As evidenced by the continuing deployment of capital, Hess and its non-operating partners are satisfied with the commerciality of the historical ROZ demonstration project.

In addition to the four projects within the ROZ at the SSAU, seven other ROZ projects are underway. Figure 2.5 maps out and Table 3.1 summarizes those projects for the reader. As far as is known, these eleven ROZ projects are the only active ROZ EOR projects in the world today. Note that in the Table, several new Permian Basin projects are slated for initiation for 2012 through 2014. Timing of new ROZ activity is dependent on CO_2 supply availability. The accelerated ROZ deployment has clearly created unprecedented supply problems; many other unlisted projects await CO_2 availability to begin implementation. In addition, there is such significant worldwide interest in the Permian Basin projects that we would expect that ROZ projects, some CO_2 EOR and, perhaps, some first-of-a-kind chemical EOR ones will soon be implemented in the Middle East and perhaps elsewhere. Note that the last project shown in Table 3.1 is not identified by operator name but is reportedly planned to be a first, a "greenfield" project in the Permian Basin and one that will be implemented in a region where all injector and producer wells will be new drills, i.e., no main pay zone is present.

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as of 2012

TABLE 3.1: ON-GOING AND PLANNED ROZ CO_2 EOR PROJECTS IN THE PERMIAN BASIN REGION OF THE U.S.

	Type and operator	Field	State	County	Top MPZ Depth, (ft)	Pay zone	MPZ Start Date	ROZ Start Date
	Active CO_2 miscible							
1	Chevron	Vacuum San Andres Grayburg Unit	NM	Lea Co.	4,550	San Andres	2007	2007
2	Fasken	Hanford	Tex.	Gaines	5,500	San Andres	7/86	8/09
3	Hess	Seminole Unit-ROZ Phase 1	Tex.	Gaines	5,500	San Andres	7/83	7/96
4	Hess	Seminole Unit-ROZ Phase 2	Tex.	Gaines	5,500	San Andres	7/83	4/04
5	Hess	Seminole Unit-ROZ Stage 1 Full Field Dev	Tex.	Gaines	5,500	San Andres	7/83	10/07
6	Hess	Seminole Unit-ROZ Stage 2 Full Field Dev	Tex.	Gaines	5,500	San Andres	7/83	5/11
7	Legado	Goldsmith-Landreth Unit	Tex.	Ector	4,200	San Andres	8/09	8/09
8	Occidental	Wasson Bennett Ranch Unit	Tex.	Yoakum	5,250	San Andres	6/95	2000
9	Occidental	Wasson Denver Unit	Tex.	Yoakum	5,200	San Andres	4/83	1995
10	Occidental	Wasson ODC	Tex.	& Gaines	5,200	San Andres	Nov-84	2005?
11	XTO/ExxonMobil	Means	Tex	Andrews	4,500	San Andres	Nov-83	1/12
	Planned CO_2 miscible							
12	Conoco	East Vacuum (GSA) Unit	NM	Lea Co.		San Andres		2012
13	Chevron	Central Vacuum	NM	Lea Co.		San Andres		2012
14	XTO	CA Goldsmith	Tex	Ector	4,200	San Andres		2013
15	Tabula Rasa	East Seminole	Tex	Gaines	5,400	San Andres		2013
16	SandRidge Tertiary	George Allen	Tex	Yoakum	4,900	San Andres		2012
17	Undisclosed	Greenfield ROZ	Tex	Undislosed		San Andres		2013

4.0. ROZ BACKGROUND AND KEY EVIDENCE FOR THE PRESENCE OF ROZS

Waterflooding of Permian Basin reservoirs by engineers and geologists has been a common practice for almost 60 years. One would think that, after such a long period of time, everything there is to know about oil and water movement in Permian Basin reservoirs would be well known. New findings like the ones presented herein are illustrating that much is yet to be learned. As the tectonic history is reconstructed, a new framework for understanding illustrates that Mother Nature has been water flooding portions of our reservoirs for over 60 million years. We are only now beginning to understand the impact Mother Nature had on Permian Basin reservoirs and the potential for EOR and carbon capture use and storage (CCUS) this creates. Estimates (Koperna and Kuuskraa (2006)) have made indicates that there are 5 to 15 billion barrels of CO_2 EOR recoverable reserves in ROZ's around the basin. What brings even more attention to this resource is the possible associated CO_2 storage capacity in these targets, perhaps doubling the value of the ROZ reservoir assets.

Over the 85 year history of exploration and production in the Basin, there has been developed a lot of "common knowledge" about the reservoirs. This begins with the understanding of the interval beneath the main pay intervals. Starting near the original oil/water contact (OWC), which can vary in definition from property to property, there is a transition zone (TZ). Engineers and geoscientists all recognize that within the TZ there is a depth below which the old managerial onion skin memos said "don't drill any deeper than xxxx feet you will produce big water." Early workers recognized that the formation had oil saturation in that interval, that it often contributed to production, and that it "varied in thickness." Others were heard to say that where there are tight rocks beneath the oil/water contact, there are longer TZs. It was also a generally held belief that the TZs extend to the Base of Saturation of Oil (BOSO) and if a reference was made to a Residual Oil Zones (ROZ's), it was synonymous with the TZ theory of oil and water saturation "smearing." With industry's evolving understanding, much of this "Common Knowledge" about the TZs is at least partially in error.

A new paradigm is developing. Driven by both research and EOR field developments, it begins with the realization that there are thick intervals in the lowermost portion of our reservoirs and large areas outside our established fields that have been swept by "Mother Nature's Waterflood." The theory requires a recognition that a very large paleo trap existed, much thicker and larger in extent than the scattered remaining main pay zone fields. Those fields were isolated from the natural sweep because of closure on top of the porous intervals. Fortunately, these ROZ's have the same saturation characteristics as mankind's mature waterfloods in the swept, main pay intervals.

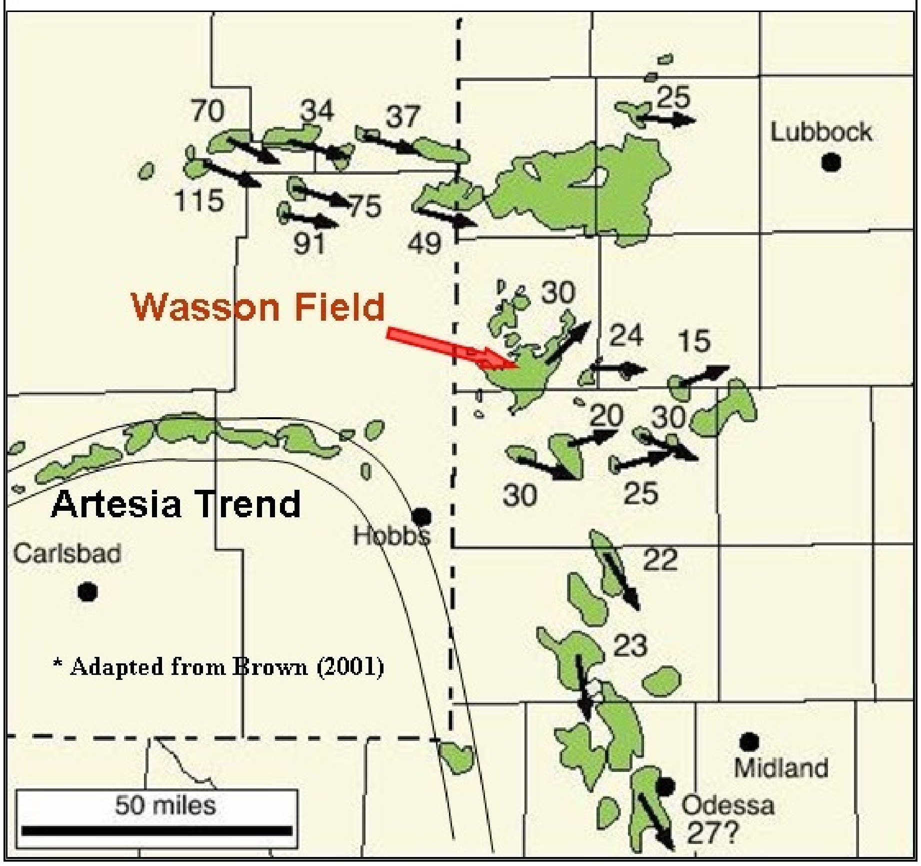
In the Permian Basin the San Andres formation has the reputation that it seemingly always yields good "shows" of oil and gas. This observation occurs both beneath established producing fields and in areas away from production. These are the ROZs and are often are interpreted as oil productive from the shows in the cuttings and porosity readings and oil saturation calculations from wireline logs. As a result, well completions are often attempted with frustrating results. Many yield only black sulfur water. The nature of an ROZ is that it will not yield oil in commercial quantities in either primary or secondary operations. The oil that is present takes exposure to an injectant to alter its properties to make it moveable.

In case after case and area after area, the characteristics of ROZ's seem the same. There is: good odor, cut, fluorescence, and gas shows in samples, calculations of 20% or much higher oil saturations from logs, 15-40% oil saturation from core tests; predominance of dolomite over limestone; and production of sulfur water on DST's or completions.

During the course of the past 20 years, a number of successful CO_2 EOR projects in Permian Basin fields have been slowly changing the perception of the potential of ROZ's. What has been learned is that commercial oil can be produced from ROZs in the intervals below the main pay zones. Coincident with that engineering progress, scientific research into the development and characteristics of "Mother Nature's Waterflood" has led to a better understanding of the past, present and future of ROZ's. That history goes back to the landmark work of Hubbert (1953) but let's begin to recount the progress more recently with the work of two Permian Basin geologists.

During the 1990's, Alton Brown documented the effects of hydrodynamics on Cenozoic oil migration in the Wasson area and elsewhere on the Northwest Shelf. Using available data, Mr. Brown proposed hydrodynamics as a more reasonable mechanism to explain the presence of an OWC tilt of 30' per mile in the Wasson Field in Yoakum County (Fig 4.0). He believed that the movement of meteorically-derived waters fifty to hundreds of miles distant was a better explanation than capillary "smearing" of oil saturation from top down. He also postulated that the hydrodynamic charge model also explains that the thick (250-300') ROZ in the field is a relic from a previous (paleo) static trapping condition. He went on to document the presence of tilted OWCs in a number of fields on the Northwest Shelf and Central Basin Platform. It has since been postulated and now recognized that the amount of tilt is a function of the flow path (the "fairway") and proximity to a source of meteoric recharge, and that, in the Permian Basin at least, the direction of flow is controlled by regional shelf to basin relationships.

Figure 4.0: Distribution of Tilted Oil-Water Contacts in the Northern Shelf and Central Basin Platform Areas of the Permian Basin*



At about the same time, another researcher working while at Chevron, Bob Lindsay, looked at outcrop-to-core-to-production relationships in San Andres and Grayburg fields and documented meteorically-driven water sweep and the development of thick columns of residual oil in a number of fields on the Central Basin Platform. He recast the sweep history by documenting that there were two key periods of oil migration (post-Permian & Cretaceous/Tertiary) commonly proposed for Permian fields in the basin, resulting in the establishment of “Filled” structural and strato-structural traps. Lindsay envisioned massive recharge of meteoric waters through Permian shelf carbonates and into the subsurface during the mid- to late-Tertiary as a result of uplift in the Rio Grande Rift trend to the west in New Mexico. The lower portion of established oil columns in a number of fields was swept out of the structural and strato-structural traps. The later extensional development of the Basin and Range structures west of the Guadalupe and Sacramento Mountains reduced the “hydraulic head”. Some oil was left behind on the downdip flanks, and meteoric related waters introduced “bugs” which further reduced the volume of oil. Following the reduction in head, and tectonically associated enhancement of structure, new oil/water contacts were established in the fields with significant thicknesses of partially oil saturated reservoir now below the oil/water contact.

As we flash forward to the present, the major product of this RPSEA sponsored study is the development of a more complete model of the system that created “Mother Nature’s waterfloods” and beginning the technology transfer that moves the industry away from the more limited TZ model. The effort could not address the entire Basin at such an early stage so an area was chosen for emphasis. For reasons stated in the Introductory section, some areas of interest were excluded. The focus was subsequently placed on identifying/defining what has become known as the Artesia trend of the middle to Upper San Andres formation along the Northwest Shelf San Andres to west Central Basin Platform San Andres shelf margin to the Pecos County sulfur mines. The team has gathered data from a variety of sources which are described in detail in the next section.

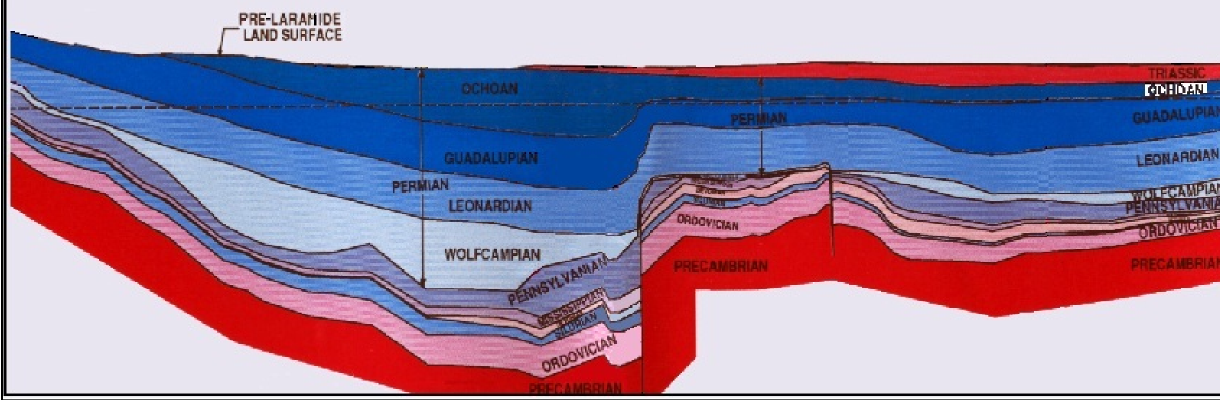
The data gathering was accomplished in order to simulate the hydrodynamic flow conditions that occurred in the geologic past. Those conditions created the sweep of the paleo traps which led to the formation of extensive ROZs along the Artesia trend. Arcadis, an environmental firm, was recruited to conduct the modeling study. They possessed a long history of groundwater studies in the Permian Basin and proposed to use a public version of ModFlow, a U.S. Geological.Survey developed, finite-difference ground water modeling program with regional capabilities to model the paleohydrodynamics of the region using the oil field data the team collected.

4.1 Geographic Distribution of ROZ Fairways

The presence of thick, ROZ’s in the Permian Basin is only possible because there are regional pathways of migration for fluids, both water and oil, to flow into through and away from traps. Early oil migration into the traps following well defined source to reservoir pathways has been well documented in the basin. In most cases, these pathways involve basin to shelf migration, which can be proven to have been active as early as the end of the Permian, and as late as the Mid Tertiary. The hydrocarbons were trapped in Leonardian and Guadalupian carbonate and clastic shelf reservoirs by the updip loss of porosity and permeability, and sealed by impermeable clastic, carbonate or evaporite intervals above. The accumulations are typically trapped along strike by variations in paleo-structure at the top of porosity and along trend.

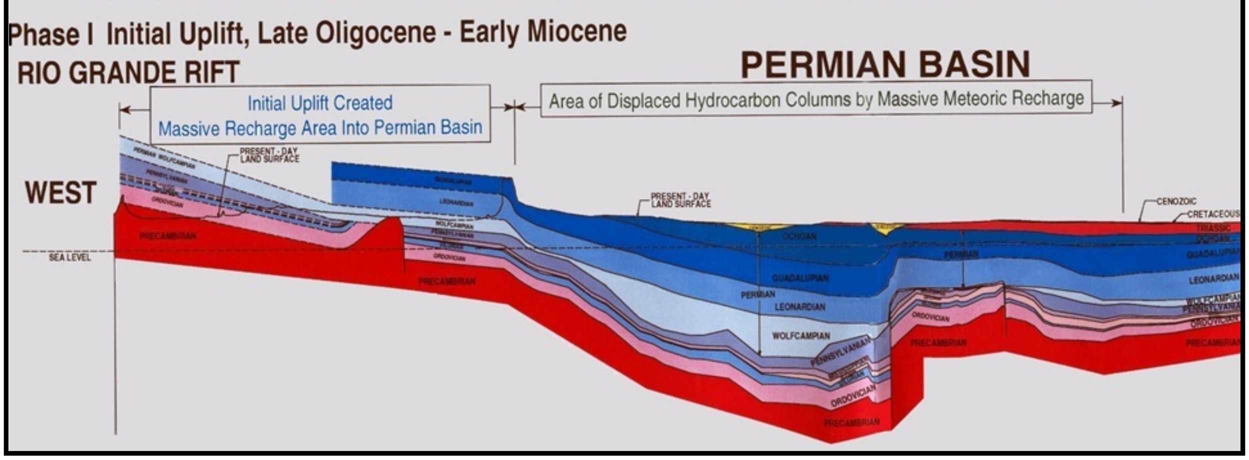
The model for regional flushing of all, or portions, of these reservoirs, developed herein and by Lindsay and Brown (1998, 2001, 2004), identifies the pathway of eastward migrating meteoric waters moving down dip away from the recharge areas between the present day Rio Grande Rift and what is now identified as the western margin of the Northwest Shelf of the Permian Basin (prior to the Laramide orogeny, the Permian Basin extended much further to the west). The late stage (Tertiary), lower salinity waters were following regional aquifer pathways that were entirely different than those followed by the oil during migration into the reservoirs. The initiation of this meteoric-driven flushing was coincident with initial phase of Rio Grande Uplift and Tertiary volcanism in the Trans Pecos (Fig 4.1).

Figure 4.1: Post-Subsidence Tectonic Phase of Permian Basin Development (From Lindsay (2001)



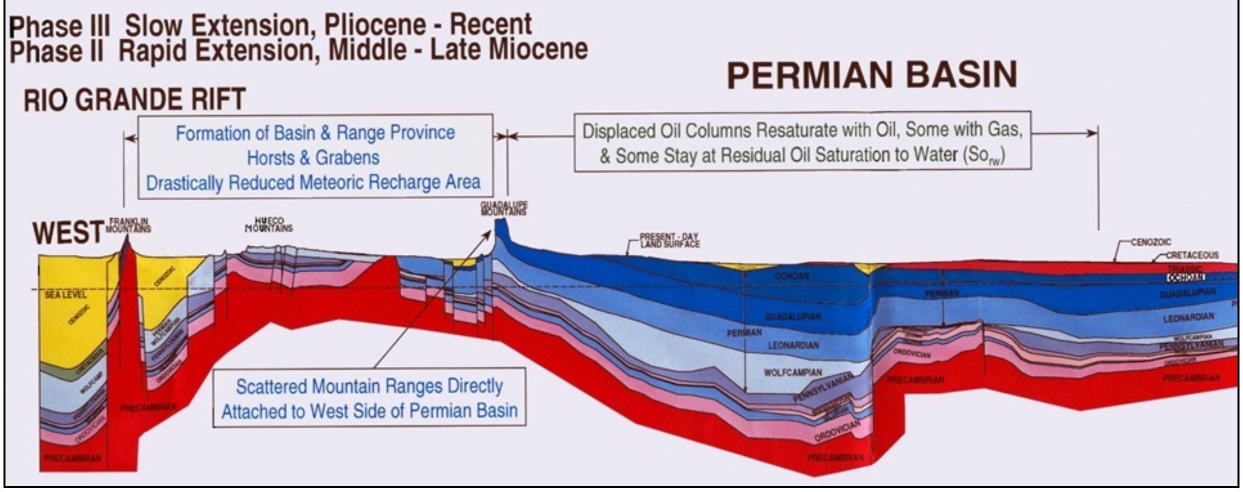
Late Mesozoic-Early Cenozoic Laramide Tectonism (70-50 Mya) caused initial uplift of the western portion of the Permian Basin, and initiated the major flushing of oil out of existing traps (Fig 4.2).

Figure 4.2: Initial Uplift (Maximal Recharge) Phase in the Permian Basin (From Lindsay (2001)



The major mobilization of hydrocarbons out of existing reservoirs occurred during Basin and Range Tectonism, beginning ~30 Mya, with a very large meteoric recharge event occurring during the Late Oligocene-Middle Miocene (20-30 Mya) as the Rio Grande Rift was initially uplifted (Fig 4.3).

Figure 4.3: Extensional Phases and Reduction of Hydrodynamic Gradients in the Permian Basin (Lindsay (2001))



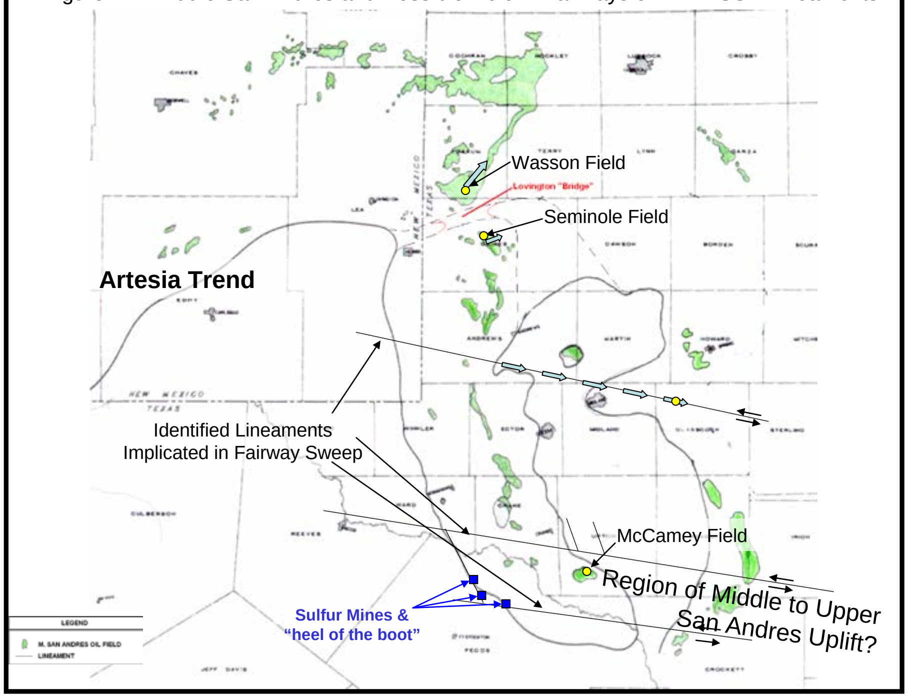
The original recharge surface extended essentially from the area west of a line from El Paso to Socorro, NM to a line from Carlsbad to north of Roswell. This potential recharge area was half the height of the Permian Basin. During that time, large volumes of initially fresh but soon mixed waters swept through the porous and permeable reservoirs. The mixing occurred rapidly so that the majority of the flushing was with relatively saline subsurface waters, and referred to as "Mother Nature's Waterflood" (MNW). The MNWs swept oil out of the plaeo entrapments and created the ROZs seen in the Permian Basin today. These Residual Oil Zones beneath existing fields have become known as "brownfields" since the wells exist and are only needed to be deepened to apply CO_2 EOR techniques to the ROZs. This MNW process resulted in the re-positioning and tilting of the oil-water contacts which are now identified and described in the Permian reservoirs in modern times.

In the Middle-Late Miocene this recharge surface was beginning to be pulled apart as the Rio Grande Rift underwent extension along the Mesilla – Palomas Bolsons and eastern Basin and Range extension expressed as the Hueco Bolson – Tucumacari Basin and Salt Flat Graben-Marfa Basin. The development of the Salt Flat Graben - Marfa Basin left very small recharge areas to the east, such as the Guadalupe, Sacramento, Apache, and Glass Mountains. These areas continue to recharge meteoric-derived water into the subsurface to today. This process still occurs along the "Capitan Aquifer", and through the Northwest Shelf Leonardian and Guadalupian but likely at reduced influx rates and pressures.

The water pathways of flushing would have to have followed zones of porosity and permeability. Several different pathways exist within the major oil producing formations along carbonate shelf trends wherein the waters would be flushing oil out of paleo traps along the productive trends. The Leonardian and Guadalupian shelf and shelf margin carbonates serve as both the pathway of migration for the flushing waters and as the sites for the majority of the reservoirs that have been impacted by the sweep. Because of the flushing waters, one must therefore think of the Leonard and Guadalupian shelf carbonates and clastics as regional, deep and highly saline aquifers. These regional aquifers, which, on occasion are hydraulically and vertically connected to oil and gas entrapments, were several and following different pathways east to the Central Basin Platform (CBP) and then south along the eastern and western margins of the CBP and northeast along the margin of the Texas portion of the Northwest Shelf.

For the recharge to have impacted the reservoirs on the Central Basin Platform, this requires that there be a permeability trend or trends that cross the San Simon Channel which separates the Northwest Shelf from the northern end of the Central Basin Platform (Fig 4.4). The completion of the Artesia Fairway requires that there be a pathway across the San Simon Channel established during the time of the San Andres formation deposition. Correlations from the Northwest Shelf thru the San Simon Channel to the Central Basin Platform confirms that by the end of the lower San Andres/ Early Guadalupian, the channel was filled in by debris from both north and south and that the pathway was established (called the 'Lovington Bridge' in Figure 4.4), allowing the flushing fluids to move oil along the length of the trend. The middle and upper Guadalupian Capitan Reef complex, later in age and also aligned along the margin of the Northwest Shelf and the western margin of the CBP also serves as a separate pathway of migration of the meteoric recharge. Section 7 will provide a more detailed discussion of the trends, hydrodynamics and provide maps of flow to aid the reader. NOTE suggest changing the backgroup of the labels on the figure. At this scale they are not legible.

Figure 4.4: Middle San Andres and Possible Role in Fairways of NNW-SSE Lineaments



Along the eastern margin of the Central Basin Platform, it has been postulated herein and adapted from Lindsay, 1998 that the oil remigrated, at least in part, from the closures in the shelf carbonates eastward down dip into the shelf margin and slope carbonates and interbedded clastics. When the meteoric recharge "head" was reduced during the creation of the Hueco, Tularosa and Salt Flat Grabens, a portion of the oil was able to reverse direction and migrate or "snap back" into the crest of some structures/closures, but not all of them. That oil which did not re-migrate into the closure and, by far, the bulk of the displaced oil was likely carried along fairway trends to finally leave the system at exit points. However, much of the oil remained behind as residual oil in reservoir. Some was used by bacteria in the conversion of anhydrite and for the creation of the H_2S in the oil and water systems as well as in some sulfur deposits as at the southern end of the Central Basin Platform.

On occasion, gas took the place of part of the original oil column. But, in the bulk of the fairway, neither gas nor mobile oil re-saturated the closure and the paleo structural traps were left at residual oil saturation of waterflood, with no primary or secondary waterflood potential. These have become known as "greenfields" owing to their lack of producing well infrastructure and are extremely common over wide areas of the Central Basin Platform and Northwest Shelf.

4.2 Need for Exit Points

To develop the kind of meteorically-driven flow necessary to sweep the proposed volumes of oil out of the paleo structures requires a through flowing system and exit point(s) for each of the fairway systems. Considerable additional work is required to identify and better define the fairways but there are a number of potential exit pathways and points associated with regional NNW-SSE trending lineament (fracture) systems across the Central Basin Platform and Midland Basin (see Fig. 4.4). Another potential pathway crosses from the southern end of the Central Basin Platform eastward across the Ozona Platform from the vicinity of the Yates Field. The exit point for sweep on the western side of the Central Basin Platform is believed to be vertically upward through a trend of upper Permian sulfur deposits in northern Pecos County (see Fig 4.5). The exit pathways from the Texas portion of the Northwest Shelf trend are postulated to follow a series of San Andres shelves and shelf margins that developed as the northern end of the Midland Basin closed during the San Andres. Flow pathways from the northern end of the Central Basin Platform would follow either the San Andres/Grayburg shelves southward along the eastern margin of the Central Basin Platform or the upper San Andres or Grayburg shelf margins where they cross the Midland Basin.

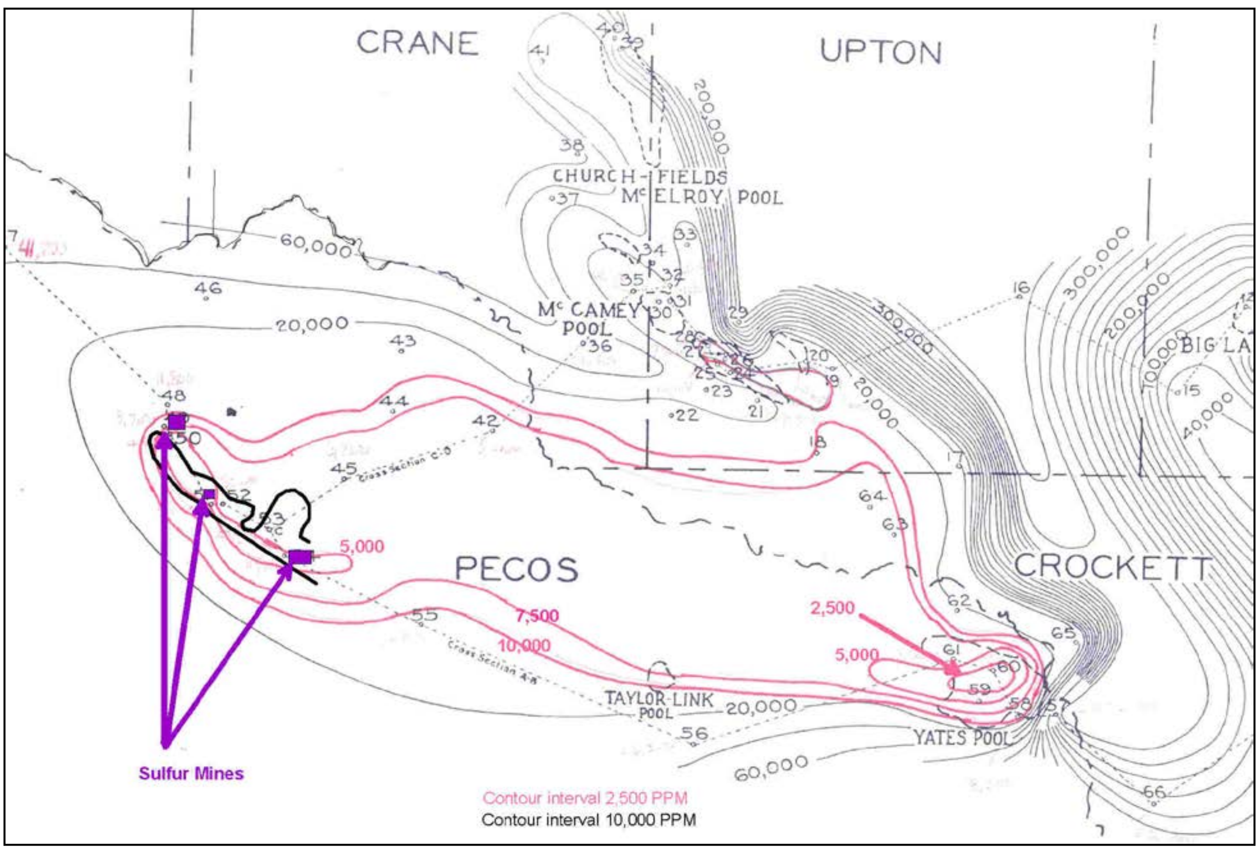


Figure 4.5. Location of sulfur mines along exit pathway for “Mother Nature’s Waterflood”. Modified from Berger and Fash, 1934.

Another important component of this model of flow is the presence of choked discharge pathways (the ‘Hose Nozzle Concept’). If the sources for the flow and the flow pathway are now established, we also need discharge points in order to have movement of the flushing waters. And is the flow dominated by the flow characteristics or is it restricted at points along way? The ‘Heel of the Boot’ of the Central Basin Platform is the location of a number of inactive sulfur mines. These large sulfur deposits in northern Pecos County are believed to represent one (possibly temporal) exit point on the Central Basin Platform for the flushed oil and waters. The generation of the sulfur and its host limestone is considered to be epigenetic and to have formed biogenetically within a calcium sulfate environment (McNeal and Hemenway, 1972).

There are other documented sulfur deposit related exit points on the Eastern Shelf and appear, in certain cases, aligned with the basement lineaments.

These deposits are the result of the biogenic processes, the mutual occurrence of water, oil and a source of sulfur.

$CaSO_4$ + Hydrocarbon + water flushing → $CaCO_3$ + H_2O + H_2S

Water flushing – from the meteorically driven system
Flushing Oil (Replenishing the Food for the Anaerobes)
Sulfur – from replacement of sulfur by carbon in the anyhydrite as the source of H_2S (and sour oil/gas)

The depletion of anhydrite and the localized sulfur deposits (product-of-reaction, residue) are:

1) proof of oil displacement, fairways of water and oil movement,
2) proof of oil 'consumption', and
3) clues to the pathways for the flushing system.

The Fort Stockton Sulfur district contains a series of large sulfur deposits found in northern Pecos County at the crest of the regional anticline formed at the edge of the Delaware Basin (Figure 7.9). The mines occur within the porous limestone facies in the evaporitic Salado Formation of late Permian, which overlies the San Andres Formation of the earlier Permian. These mines are believed to represent exit pathways on the Central Basin Platform for the flushed oil and meteoric waters that flowed through the Artesia Fairway. Thickness maps of sulfur ore bodies suggest the presence of at least nine discharge points through which groundwater flow occurred. Sulfur mines were located at three of these locations as noted in Figure 7.9. Based on TDS values of groundwater in the Rustler, vertical discharge may have taken place up to the Rustler where lateral migration to the east and out of the Fairway could have occurred (Jones et al., 2011). Reference missing from list of references, please add it.
For further analysis of the source of sulfur see section 7.2.5.3

4.3 Mapping of Fairways - Not all fields have thick ROZ's

The McCamey Field in southern Upton County (see Fig. 4.4), which is productive from both the San Andres and Grayburg, has a +/-50' ROZ below the established oil/water contact. This field lies on the shelf margin between the McElroy and Yates Fields, both of which are reported to have thick ROZ's. It is believed that the oil column in the highly porous San Andres paleo-topographic trap and the overlying and fringing Grayburg strato-structural traps in the McCamey Field were initially filled to the spill point. It appears that when the flush waters swept through the area, the McCamey Field was largely unaffected by the sweep as there is such a thin Residual Oil Zone below the present oil/water contact and the reservoir appears to be filled to the spill point. One interesting note is that the ROZ is composed primarily of dead oil or solid hydrocarbon residue in the highly karsted and porous San Andres portion of the reservoir suggesting that perhaps the lowermost portion of the reservoir was efficiently swept and when the hydrostatic head ceased to operate, oil did refill the reservoir to the spill point. It is not known if the McCamey Field is the only major example of a thin ROZ bearing field on the Central Basin Platform. It is anticipated that this and other questions concerning trapping, sweep and re-mobilization of oil will be addressed during a later study. There is 200’ of “post Brushy Canyon Bypass Surface” (missing section) that is partially above the O/W at McCamey.

On the east side of the platform, the primary pathways would have been the lower and middle Guadalupian upper San Andres and Grayburg shelf carbonates, which are also the primary reservoirs. Many of the major San Andres and Grayburg reservoirs on the eastern side of the Central Basin Platform have thick ROZ zones. The upper Guadalupian rocks were typically deposited in sabkha and fluvial environments, are devoid of significant production, and would not have served as pathways for sweep waters. In many fields, the ROZ is mostly, if not completely confined to the San Andres portion of the reservoir.

On the western margin of the platform, the pathways would have included the marginally productive upper Leonard Clearfork, Glorieta, lower and middle Guadalupian San Andres and Grayburg, and also the Goat Seep and Capitan Reefs of the middle and upper Guadalupian. This is believed to be a result of efficient sweeping of the hydrocarbons out of existing traps. The Glorieta, San Andres and Grayburg shelf carbonates typically have good shows and stain but produce 100% water. The up-dip ends of the porous shelf facies are typically stratigraphic traps with reduced porosity and permeability. These will not be efficiently swept but the meteoric waters and will retain higher oil saturations than the swept ROZ’s. Is it possible to determine the original ROZ S_w by determining the S_w of the lower permeable portions of a reservoir and assuming sweep isolation?

Brown has postulated that the pathway along the Texas portion of the Northwest Shelf has resulted in the development of both thick ROZ’s and tilted oil/water contacts in a number of fields. Both Upper Leonard and lower Guadalupian shelf carbonate reservoirs have been affected by the sweeping of hydrocarbons with a number of fields possessing thick ROZ’s. The presence of tilted oil/water contacts, higher on the south or west, lower on the east or north, in a number of fields suggests the water flows were still active at the time of discovery.

4.4 UpDip Low-Perm vs. Down Dip High Perm

There has been production established in the San Andres and Glorieta on the Texas portion of the west side of the Central Basin Platform. These fields, however, are small and are located in the low porosity and permeability up-dip ends of the carbonate shelves where they transition into the anhydrite-rich tidal flats and sabkhas. These fields have high oil saturations (70-80%), and it is proposed that the more porous and permeable shelf carbonates down dip originally had similarly high oil saturations, but are now at residual to MNW (25 – 35% oil saturations).

Two important pieces of information can be gleaned from this. First, it might be possible to estimate the original So in the swept intervals by calculating the So in the up dip, tight portion of the reservoirs and projecting it down dip into the “swept” portion of the reservoir. Second, estimation can be made of the original oil/water contact in the more porous portion of the reservoir by identifying the oil/water in the tight up dip reservoirs as assuming a single oil/water contact was present across the entire “field”. This might assist us in identifying the paleo or “relic” O/W. The paleo OOIP can then be determined.

4.5 Water Chemistry

Changes in pre-modern waterflood water chemistry in the trend areas will be detailed as they are thought to be a key indicator of the effect of water mixing from the meteorically driven recharge and the development of thick ROZ's. It is almost universally observed now that the water chemistry in the fields within the ROZ has been modified as a result of a) microbial activity (sulfate enrichment) and b) the mixing (lower salinities) through the regional aquifer. Cautionary flags are everywhere though as water salinities can be dramatically affected by the introduction of water during the waterflooding phase of oil extraction.

Many of the fields on the east side of the CBP have been documented to have different water chemistries in different producing horizons. Fields that have not been affected by flushing water will have higher salinities (we will use total dissolved solids (TDS) as the metric). A study done in the early 1930's documented very low TDSs (<20,000 PPM) in the Grayburg and San Andres reservoirs in different fields on the southern end of the CBP, extending from northern Crane County, north of McElroy, to northeastern Pecos County, west of the Taylor-Link field. At Foster South-Cowden, in central Ector County, the pre-waterflood TDS for the upper Grayburg (27,000 PPM) is significantly lower than the TDS in the lower Grayburg (37,000 PPM) and lower still than waters in the upper San Andres (62,000 PPM).

On the western side of the platform in the North Ward Estes area in central Ward County, The uppermost Glorieta is productive from the thin bedded, shallow marine to tidal flat facies, while the porous and permeable open marine intervals typically has excellent show but produces 100% sulfur water.

4.6 What Does a Residual Oil Zone (ROZ) Look Like?

This RPSEA sponsored research has expanded on the initial DOE/NETL work by Melzer (2006) and ARI (2006). It has documented the evidence for, and characteristics of, ROZs below major San Andres reservoirs in the Permian Basin. There is significant anecdotal evidence for the presence of ROZs from exploration wells in "goat pasture" areas adjacent to and at distance from existing fields, in what has become known as "Greenfields." After discussions with a number of exploration and production geologists, and having viewed cores, logs and mud logs from a number of documented ROZs, some characteristics are beginning to stand out as the properties of, and evidence for, the presence of a ROZ. The rock and fluid properties are the same whether looking at Brownfield or Greenfield ROZ's. These ROZ's are now being very privately documented over wide areas of the northern Central Basin Platform (CBP) and Northwest Shelf and, with this study, on the west side of the CBP. In addition to their extensive presence in the San Andres, our study has identified the presence of ROZ's in the Abo (Wichita Albany), Lower and Upper Clearfork, Glorieta/San Angelo and Grayburg. Additionally, ROZ's are believed to be present in the basinal sand reservoirs in the Delaware Basin.

As discussed previously, ROZs have many of the same characteristics of the swept portions of a mature waterflood. Mother Nature is a patient and efficient production engineer. The lateral flushing took place post oil emplacement. It is believed that the water volumes passing through a reservoir during MNW lateral flushing generally exceeded those of a conventional waterflood. But there were some biogenic processes at work counteracting the tendency to drive residual oil saturations (S_{orw}) to sub-economic levels. The water chemistry, residence and travel time and diagenetic changes to the reservoir over millions of years clearly have had a different impact on the reservoir than what has been observed in a modern waterflood.

Hence there are distinctive rock and fluid properties seen in the ROZs that are not present in main pays.

The observed reservoir changes can be divided into 1) rock and fluid properties and 2) production characteristics. Rock properties typical of the ROZ include: the presence of sulfur crystals associated with gypsum in the swept interval of carbonate reservoirs; evaporites that are often replaced by dolomite. sample shows of oil and/or gas (odor, cut, fluorescence in samples, and mud gas); pervasive “late-stage” dolomitization indicating extensive exposure of the rock to both oil (for the microbes) and magnesium for the alteration of the calcite; core with non-primary or secondary productive oil saturations (10-50%); the presence of a pervasively dolomitized interval (PDI) which may be 100s of feet thick and include the ROZ and the interval beneath the ROZ; porosities and permeabilities that can be higher in the ROZ than in the pay zone as a result of the overprint of late stage dolomitization; solution-enhanced fracture and moldic porosity in the ROZ that does not display oil or Solid hydrocarbon Residue (SHR) on the void faces; and expectations that carbonates in the ROZ will have extremely depleted d13C values (yet to be documented).

ROZ fluid properties include: overwhelmingly high water cuts (typically ‘skims’ of oil) during drill stem testing (DST) or attempted completions; log calculations that suggest producible hydrocarbons; mixed or changed wettabilities; hydrogen sulfide–rich waters produced in DSTs or attempted production tests; spotty oil stain/saturations near the base of the ROZ; the presence of sulfur/oil compounds in the produced waters of the ROZ; and historically documented tilted oil/water contacts. Despite encouraging sample shows and promising core saturation measurements, oil on the pits, some oil recovered on DST, and encouraging log calculations, these ROZs intervals will always be failures in primary or secondary production attempts.

Production characteristics include: some contribution to primary and secondary production from the Transition Zone at the top of the ROZ; production from ROZs with the similar oil/water ratio characteristics as mature waterfloods; main pay/ROZ transitions associated with stratigraphic breaks; the same economics as a successful MP CO_2 flood depending on the oil saturation profile in the ROZ (SW in the 20% - 49% range will have a higher likelihood of economic success).

As will be seen in Chapter 8, the project modeling of the “Artesia Fairway” has yielded interesting results: the number of pore volumes of flushing range from 19 to 51 based on a porosity that ranges from 6% to 16%, over the time frame of 15,000,000 years. The low flow portions of the San Andres had flow rates that ranged from 0.8 to 2.1 feet per thousand years with the core of the high flow zone having a flow rate that ranged from 317 to 847 feet per thousand years and the total flow volume is estimated at 6.54683E+12 cubic feet. Flow rate through the high permeability zone was could be as much as 6.21 GPM; total flow through the San Andres section was 7.23 GPM.

5.0. MINING THE DATA

5.1 Sources of Water Chemistry Data

Water chemistry data for producing fields and Brownfields and Greenfield ROZs is not typically publicly available. However, TCEQ and USGS do contain useful water data.

The USGS produced water database is found at:
http://energy.cr.usgs.gov/prov/prodwat/.

The USGS produced water database presented at this web site is a revision of a database originally compiled at the DOE Fossil Energy Research Center that was located in Bartlesville, Oklahoma. The USGS modified the original database by removing redundancies, verifying internal consistency and adding information to the fields that describe the location, geologic setting, sample type, and major ion chemical composition. A preliminary version of the revised database, a description of the review methods and illustrations of the contained information are presented.

The TCEQ Ground Water database can be found at:
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm

The Texas Water Development Board's (TWDB) Groundwater Database is also available and updated monthly: Reports have been generated and broken out by county. There are five reports per county that combine the most often needed information from all of the database tables. The reports are the Records of Wells, Water Levels, Water Quality, Infrequent Constituent Water Quality and Cooperator Infrequent Constituent Water Quality.

The first part of the modeling effort required definition of the fairway of sweep. Once the general fairway trend was selected, a major effort to collect subsurface data including water data. Tables 5.1 and 5.2 outline the water data acquisition effort for both the USGS and drill stem data. This chapter will describe the process with subsequent chapters summarizing the hydrodynamic modeling effort and results.

TABLE 5.1: ATTRIBUTES OF WATER STUDY (1)

IDENTIFY FAIRWAY OF INTEREST SELECT COUNTIES TO EXAMINE	
	KEY SOURCES OF DATA FOR THIS STUDY
IDENTIFY SOURCES OF WATER DATA, CHECK AVAILABILITY	USGS Produced Water Data Base (Ref 1) Commercial Drill Stem Test Data (Ref 2)
MERGE & VERIFY USGS WATER DATA WITH 3rd PARTY* AVAILABLE WELL RECORDS	
Data Set was Originally Designed to include:	
Water Composition/Constituents	Always included
Sampled Formation	Always included
Sample Depth	Always included
Sample Date	Always included
Data Source	Always included
And the well identifiers (sometimes missing)	
(NM better than Tx in DataBase)	
1) API Well Number	Occassionally included
2) Latitude, Longitude (Location)	Occassionally included
3) Well Number and/or Lease Name	Occassionally included
4) Field Name and Field Number	Occassionally included
5) Survey, Blk, Section No.	Occassionally included
{or, alternatively, Township, Range, Sct #}	
USGS Data Set Did Not Include Necessary Data:	
Operator Name (much of data acquired with an agm't to hide operator name)	
Actual Well Spot Location	
Completion Date of Well	
Total Depth of Well	
* 3rd PARTY PROVIDERS ARE THE STATE REGULTORY (SR) DATA BASES, COMMERCIALLY AVAILABLE LIBRARIES (MEL**) AND INDUSTRY DATA BASES (HPDI***)	
** MIDLAND ENERGY LIBRARY OR SUBSURFACE LIBRARY (3RD Party Commercial)	
*** 3rd Party Production Data Bases Like HPDI {used here} or HIS or Lasser	

TABLE 5.2: ATTRIBUTES OF WATER STUDY (2)

IDENTIFY FAIRWAY OF INTEREST SELECT COUNTIES TO EXAMINE	
	KEY SOURCES OF DATA FOR THIS STUDY
GO TO 3RD PARTY* SOURCES OF DRILL STEM TEST DATA, CHECK AVAILABILITY	Commercial Drill Stem Test Data (Ref 2) Well Files from Area Active Companies
Data Set Usually Includes:	
Operator Name	Always included
Well Number	Always included
Lease Name	Always included
Sampling Depth Interval	Always included
Sampling Date	Always included
Formation Tested	Always included
Field Name	Always included
County	Always included but Counties often misidentified
And the Needed Data (usually missing)	
(NM better than Tx in DataBase)	
API Well Number	
Actual Well Spot Location	
Well Number and/or Lease Name	
Completion Date of Well	
Total Depth of Well	

* 3rd PARTY PROVIDERS CAN BE THE STATE REGULTORY (SR) DATA BASES, COMMERICIALLY AVAILABLE LIBRARIES (MEL**) AND COMPANY FILES

5.1. Selecting the Study Fairway

The Artesia Fairway (Figure 5.1, see Appendix A-2) was chosen for the study for a number of reasons. It represents the most direct and most identifiable pathway from the Guadalupe and Sacramento Mountains. It includes a well-documented porous and permeable trend of shelf margin dolomites along the Northwest Shelf. A documented pathway across the San Simon Channel connects the Northwest portion of the Artesia Trend with the western Central Basin Platform portion of the trend. On the western margin of the Central Basin Platform there is substantial evidence of the effects of meteoric derived flushing and identified ROZ's, many without associated main pays. South of Jal, New Mexico there is only minor San Andres production, and although this limits the amount of data available, it results in a data set that is both appropriate and manageable for analysis. The presence of the sulfur mines at the southwestern corner of the platform in Pecos County also provided an exit pathway for the flushing fluids, completing the trend from source through trend to exit pathway.

A number of fields along the Northwest Shelf portion of the trend have been identified that have tilted oil water contacts, ROZ's, and pilots where CO_2 is, or is planned to be, injected into the ROZ beneath the existing Main Pay CO_2 flood. In addition, there are other Brownfield and Greenfield opportunities along the trend.

Using donated north-south 2-D seismic lines that had been shot across the San Simon Channel along the Texas–New Mexico border, and cross sections constructed parallel to the seismic lines, it became apparent that by the middle San Andres, shelf debris had filled that portion of the San Simon Channel and that the pathway of migration from the Northwest Shelf across the Channel and onto the Central Basin Platform through shelf carbonates had been established. It appears that the channel in the area of the state line was filled earliest and during the middle and upper San Andres, the entire channel was filled.

On the western margin of the Central Basin Platform there is substantial evidence of the effects of meteoric derived flushing and identified ROZ's. In the Monument to Eunice Monument South area, work by Lindsay has documented that there is a thick San Andres ROZ beneath a minor San Andres and major Grayburg Main Pay Zone (mostly in the Grayburg, although the production is comingled). He also documented that the San Andres has a sulfate rich "bottom water drive" which is sourced from the Sacramento Mountains and a sulfate poor "edge water drive" in the Grayburg, sourced from the Guadalupe Mountains. This supports the concept that the San Andres is hydrologically separated from the Goat Seep Reef (Grayburg) and therefore separate from the Capitan Reef.

South of Jal, New Mexico there is only minor San Andres production in the Texas portion of the Artesia Trend. There are, however, a number of documented ROZ's in the San Andres in the trend without associated main pays. This trend has effectively been swept of all but minor producing intervals where the permeability is so low the meteoric derived waters were unable to sweep the reservoir. Although much of the production along the west side of the Central Basin Platform is upper Guadalupian, there are a large number of wells drilled for Pennsylvanian and deeper reservoirs that provide vital information on this pathway.
The lack of large fields producing from the San Andres is actually of benefit to the selection of the trend. Although this limits the amount of data available, it results in a data set that is both appropriate and manageable for analysis.

The presence of the sulfur mines at the southwestern corner of the platform in Pecos County provides documentation for an exit pathway for the flushing fluids. Although these mines are not necessarily exit points from the system, they are along the exit pathways and provide a "grounded" data point for the model.

5.1.1 Fairway Boundaries

The delineation and refinement of the trend was an effort by a number of participants in the study. Bob Trentham identified the outline of the two low permeability flanks that acted as boundaries to horizontal flow, and the central high permeability pathway. Arcadis provided regional maps with well control onto which the outlines were plotted. ROZ team members Phil Eager and Saswati Chakraborty gathered wells to populate the cross section network. They ensured that wells with DST, well pressure tests, water chemistry, core reports, and other data were included in the cross section network.

As previously discussed, structure maps, well logs, cross sections and exploration and production knowledge of the fairway were used to identify the high permeability portion of the trend where the meteoric derived sweep has effectively reduced the oil saturation to ROZ levels. Core reports were used to document the thickness, permeability ranges and average porosities of the high permeability portion of the trend. Precise locations (latitude and longitude), and block and section locations for the wells were determined. As discussed in section 5.2, this task was necessitated by the varying precision and accuracy of the different data sets.

The limits of the fairway on the west side of the Central Basin Platform were defined as the San Andres shelf to basin transition on the basin side, and the transition from the intertidal carbonate dominated faces to the evaporite dominated sabkhas facies tract on the platform side. The participants in the project were able to approximate the limits of the fairway based on their experience in exploration and production in the area. The down dip "no flow boundary" was delineated using the commercially available land maps and structure maps, well logs and cross sections constructed for the project. In addition to porosity and resistivity logs, sample logs were used. The updip limit of the fairway was defined by the evaporite-rich Sabkha which defines the "spine" of the platform during San Andres time. This facies tract extends from the Ft Stockton Uplift on the south to the Gaines/Lea County line east of Hobbs, and separates the San Andres and Grayburg production on the eastern side of the Central Basin Platform from the Artesia Fairway on the western side.

The trend was then divided into an outboard low permeability panel, a central high porosity panel and an up dip low porosity panel. Again the structure maps, well logs and cross sections and exploration and production knowledge of the fairway were used to identify the high porosity portion of the trend where the meteoric derived sweep has effectively reduced the oil saturation to ROZ levels. Core reports were used to document the thickness, permeability ranges and average porosities of the high porosity portion of the trend. This data was turned over to Arcadis for inclusion in their model.

On the Northwest Shelf, a similar methodology was employed. The one difference is that there is no uplift area to the north of the fairway and no well-defined sabkha trend. Instead, the porous shelf margin dolomite facies transitions into tight anhydrite rich dolomites. Because of the extremely low relief on the Northwest Shelf, the sabkha facies are far to the north.
Once the fairway was delineated and the center high porosity and up dip and down dip low porosity panels documented, correlation cross sections were constructed. They were used to create structure and isopach maps to input into the model. Maps were generated and turned over to Arcadis for input into the Flow Model.

5.1.2. FAIRWAY BOUNDARIES (VERTICAL)

In addition to horizontally dividing the trend based on facies and permeabilities, the trend was divided vertically into a number of different, stratigraphically distinct, intervals within the San Andres. The middle – upper San Andres "Judkins" interval has been identified as the "flow path" (Figure 5.1.2, see Appendix).

But, before identifying the flow pathway, the entire San Andres section needed to be understood and the vertical delineation of the pathway determined. From bottom to top, the San Andres can be divided into a number of pay units, all of which are productive somewhere within the San Andres on the Northwest Shelf and/or Central Basin Platform. These are the

Holt, McKnight, Intermediate, Judkins, and Lovington. These “pay names” provide a useful terminology, because they have sequence stratigraphic importance and basin-wide correlations. This nomenclature can be tied to the Guadalupe Mountains and results in the following correlation: the San Andres in the subsurface has an Upper Leonardian L 8 & L 9 = Holt; the lowermost Guadalupian, G 1 & G 2 = McKnight Shale and McKnight; the G 3 & G 4 = Intermediate Zone(middle San Andres); the G 5 - G 7 Brushy Canyon Bypass; the G 8 = Judkins (middle- upper San Andres); and G 9= Lovington Sand and Post Lovington carbonates (upper San Andres).

The Holt is a 100-200’ thick pay zone on the Ector-Andrews portion of the Central Basin Platform, and has been applied to the interval immediately above the Glorieta. In two cores in Ward County on the west side of the platform, this zone is a deeper shelf limestone and represents the rapid transgression of the Glorieta exposure surface. The Glorieta beneath it is typically eroded thin to medium bedded, shallow subtidal to intertidal, dirty dolomite with a higher gamma ray signature but little if any shale. This interval is not productive in the Artesia Fairway, although it has ROZ potential in the P5 & P6 zones in the Slaughter Trend.

The McKnight name is used both for the shaley, transgressive (McKnight Shale) section above the "Holt" on the eastern side of the platform and the lowest major San Andres producing horizon (McKnight) in Sand Hills and other field on the "spine" of the platform. Although the correlatable interval is present area-wide, the high gamma ray McKnight Shale is restricted to the Ector and Andrews portions of the Central Basin Platform. On the Northwest Shelf, the Shale interval is represented by a deep water, non productive limestone. This interval is not productive in the Artesia Fairway.

Assuming the McKnight Shale is the maximum flood above the Holt, the McKnight ”Pay” it is the “turn around” above the shale and was deposited in deeper water on the carbonate shelves. It ranges in thickness from 150 to 350'. The top of the McKnight, is the top of the predominantly chert rich dolomitic limestone “lower” SADR. This interval is widely distributed on the Northwest Shelf and northern and central portion of the Central Basin Platform. In the Slaughter trend of the Northwest Shelf, this interval is productive. In Crane County, where the majority of the McKnight production on the Central Basin Platform is located, it tends to be dark, lower energy skeletal rich subtidal wackestones with moldic porosity and thin cycles. The McKnight is productive from a number of wells in the Artesia Fairway in Ward County but it is not productive elsewhere in the Artesia Fairway. Further study of the interval is warranted as there is a definite ROZ present in areas on the west side of the platform. The McKnight has been excluded from the flow model.

Above the McKnight is a +/-200’ thick interval referred to by the old hands as the "Intermediate Zone". The “Intermediate Zone” (Guadalupian 3 & 4) has been placed in the “upper” SADR in the BEG convention, but it more correctly should be called “middle SADR”. The top of the “Intermediate” does have an exposure surface and is probably correlatable onto the Northwest Shelf where it is possibly the Pi marker and the Brushy Canyon Bypass Surface. There may also be an exposure within the Intermediate that served as an early Brushy Canyon Bypass Surface. As yet unidentified surfaces within the Judkins may also have served as lower rank bypass surfaces. This interval can be correlated to the Residual Oil Zone in the Vacuum Field in the Northwest Shelf portion of the Artesia Fairway, however, it is not permeable or productive on the Central Basin Platform, and had been excluded from the flow model.

The upper San Andres pay zone in Crane County is the “Judkins” (G 8). It is the upper producing interval in the San Andres in the Sand Hills and many other fields on the “Spine” of the Central Basin Platform. This interval can be upward of 350-450' (if it's all present), and is an overall shallowing upward sequence with outer ramp deep water, low permeability carbonates to the west, and grading into tidal flats up dip to the east. The interval is capped by prograding tidal flats. At the top, is a major exposure surface, with karstification and, in places, significant erosion. The presence of deeper water fusulinid and crinoid-rich facies in the basal Judkins at FuhrmanMascho Field and near the shelf margin on the Northwest Shelf suggests a rapid deepening. This interval represents the primary flow path for the Artesia trend on both the Northwest Shelf and the Central Basin Platform. There are a number of marginally productive wells in Ward County which have documented ROZ's in this interval with no associated Main Pay. On the Northwest Shelf portion of the Artesia Fairway, this is the main pay, and/or ROZ and is interval documented as the flow path in the model.

The total San Andres on the "outboard" margins of the platform and Northwest Shelf is 1400-1600' thick, and include the Lovington Sand and post-Lovington intervals which are completely removed by erosion in the "Spine" portion of Pecos, Crane, Ector, and Andrews Counties, and reduced in thickness elsewhere on the platform. The Lovington Sand and Post Lovington names come from the Northwest Shelf where the Post Lovington is part of the pay zones of many of the major SADR fields. The interval above the exposure and karst surface on the Judkins is the +/-50 - 150' Lovington Sand (lower part of G9) interval which on the platform is an interval of shaley and dirty dolomite. It might also be equivalent to the Cherry Canyon Tongue in the Guadalupe Mountains. Above that is a 50 to 400' thick carbonate that I refer to as the "post Lovington". It also is heavily karsted and evaporites fill the karst reducing the extent of reservoir in many places. On the Central Basin Platform portion of the Fairway, this interval has been thinned by erosion and the porosity and permeability reduced by karstification. This interval has been included in the "low flow" portion of the upper San Andres.

Once the Judkins interval had been chosen as the primary flow path, it was identified on the cross sections and the top and base of the Judkins entered into the tops data set. The top and base of the San Andres, and the Grayburg, Queen, Seven Rivers, Yates, Capitan and Rustler tops were also entered (if available) and the entire data set turned over to Arcadis for inclusion in their model.

5.2. The Data Gathering Effort - How the Database for the RPSEA I ROZ Project Was Assembled

5.2.1 Water Data

We started with the produced-water database of Breitt & Skinner, 2002. It is a nationwide database which has been compiled, and published, by the United States Geological Survey (USGS). It has been compiled in Microsoft ACCESS software. It contains 58,706 analyses of produced waters, and is arranged numerically by Unique ID Number. We converted the Microsoft ACCESS file into a Microsoft EXCEL spreadsheet, then sorted the data alphabetically by state. We put the analyses from New Mexico (NM) and Texas (TX) into separate files. Each of the state files was sorted alphabetically by county. The counties in our area of interest were Chaves, Eddy, Lea and Roosevelt in NM; and Loving, Pecos, Ward and Winkler in TX. The produced-water sample types are reported as bailer, casing head, DST, heater treater, production test, separator, swab, tank or tank battery, unknown, water dump, or well head. We chose to concentrate on the samples from DSTs, because there was the possibility of using other sources to recover pressure and temperature data on the tested intervals. The analyses that were identified as being from Drill-Stem Tests (DSTs), were put into separate files. Those analyses are the core of our database. See Appendix A-2.

5.2.1.1 New Mexico

Of the 3,850 entries for NM, there were 94 analyses from Chaves County, 542 from Eddy County, 2849 from Lea County, and 37 from Roosevelt County.

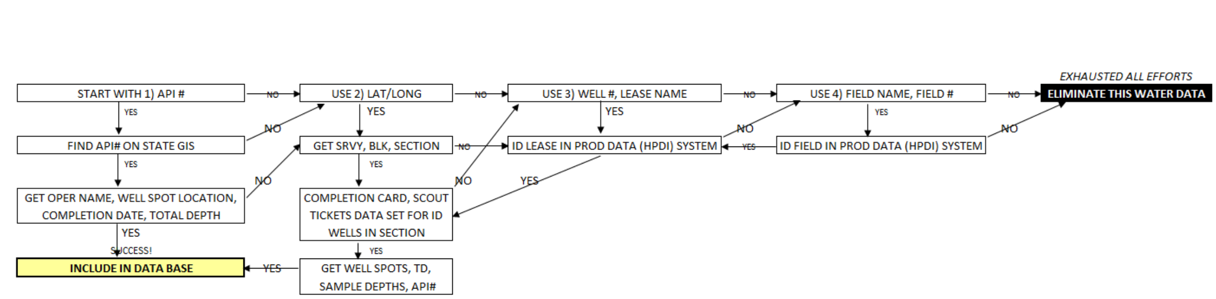
The USGS analyses from NM were easy to locate, because most were reported with an American Petroleum Institute (API) number, and included locations by township, range and section. In addition, they included well numbers and lease names. They did not include five-decimal latitude-longitude (lat-lon) or well-spot locations, operator names, completion dates, or total depths (TDs). However, with API numbers, and township-range-section locations reported, the other desired information was easily obtained from the location sets of completion cards (CCs), and scout tickets (STs), at Midland Energy Library (MEL). Once the spot locations had been determined, the five-decimal lat-lon locations were obtained from New Mexico Tech's GOTECH database. See Appendix A-2

5.2.1.2 Texas

Of the 14,589 entries for TX, there were 51 analyses from Loving County, 677 from Pecos County, 546 from Ward County, and 667 from Winkler County.

Because there were only 51 analyses, we used Loving County as a test case to perfect the data-search method. We found that the locations of the USGS analyses in TX were problematical. That is because some were not identified by API number; few were reported with section locations, and even fewer were reported with survey-and-block locations; none were reported with well-spot locations, operator names, completion dates or TDs. The analyses reported with API numbers were relatively easy to locate, primarily with the Railroad Commission of Texas's (RRCT) Geographic Information System (GIS) program on their website, or Exxon's API-number books at MEL. For analyses without API numbers, lease names and well numbers, or field names were searched in HDPI, a commercial petroleum database, which yielded survey-block-section locations. Once the survey-block-section location of a lease had been established, then the missing information was determined from the location set of CCs, and/or STs, at MEL. Once well-spot locations had been determined, five-decimal lat-long locations were obtained from RRCT's website. The order of data search for the locations of the water analyses is shown in Figure 5.2.1.

FIGURE 5.2.1: FLOW CHART FOR LOCATING PRODUCED WATER ANALYSES

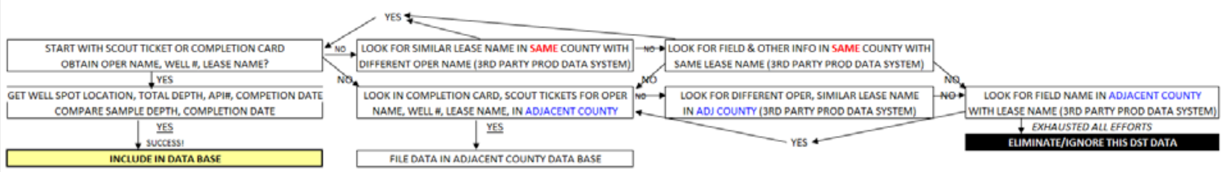


5.2.2 Additional Data

Once the produced-water database was assembled, then pressure and temperature data, as well as a few additional water analyses, were compiled from DST reports found at MEL, supplemented by CC and ST files at MEL. The DST reports contain state, county, operator name, well number, lease name, sample depth, sample date, and occasionally, formation tested and field name. The order of data search, to determine the locations of wells with DST reports, is shown in Figure 5.2.2. In most cases, this additional data was not from the same wells as the USGS water analyses, but rather from nearby wells that were completed in the same formations. The water analyses and DST reports were combined to form our database. Once the combined database was assembled, we returned to the non-DST analyses, which had been removed when we sorted for DSTs only. There we looked for additional analyses from wells with API numbers, or lease names and well numbers, which had already been located, because they had reported analyses from DSTs. Some were found, and were added to the database. See Appendix A-2

After the wells with water and DST data had been located, wireline logs for those wells were examined. The logs were correlated, and formation tops and porosity zones were picked within the stratigraphic interval of interest. All of the depth data was corrected to mean sea level datum.

FIGURE 5.2.2: FLOW CHART FOR LOCATING DRILL STEM TEST REPORTS



5.3. Drill Stem Test Data

Drill Stem Testing (DST) is the controlled sampling and measuring of a potentially productive set of strata in an open borehole using a set of tools affixed to the bottom of a drill string. The purpose of an open hole DST is to enable an educated guess of whether oil and/or gas can be produced from the tested strata in commercial quantities before the act of emplacing and cementing “long string” casing in the well bore. Ambient fluid pressure is recorded during a DST and a detailed analysis of the pressure buildup during the shut-in period can, under favorable conditions, yield a reasonably good estimate of the actual ambient reservoir fluid pressure (using the Horner relationship {see below}) and even give an estimate of the volumetric size of the reservoir. If the pressure data are favorable enough to yield a confident reservoir pressure estimate, a technique for calculating the formation permeability can be invoked. Such a calculation is subject to the veracity of certain assumptions concerning borehole and mechanical conditions. The advantage of this data is that it represents a large volume sample (vs. a small laboratory sample) and generally represents a better average of regional formation properties.

The DST analyses for this project begins with a qualitative analysis of the pressure recorder chart. Any chart which revealed insufficient time was allowed for pressure buildup during the final shut-in period was not used..

The initial flow and shut-in periods of a DST are normally not used for analysis because drilling operations normally supercharge the invaded zone of the formation with drilling fluid at pressures which are higher than ambient reservoir pressure. The purpose of the initial flow period is to release the supercharged pressure, and to partially remediate (cleanup) the formation damage caused by the invasion of drilling fluid and the deposition of mud cake on the borehole sidewall.

The reports generated by the DST tester for some of these tests (though not all tests) have in the past included a digital listing of the pressure-time measurements. The DSTs for which such listing was not included were then digitized. The digitized data were then scaled to the correct PSI and time (minutes) measurements.

Horner time units were calculated from the absolute time measurements.

$$\text{Horner time} = (T + dt)/dt$$

where T is the total amount of time during which the tools were opened for all of the flow periods and dt is the elapsed time of the shut-in period, and it is dimensionless.

The pressure-Horner time data were then imported into a statistical analysis software and the regression relationship was calculated for:

$$P = a + b * \ln(Ht)$$

where **a** is the calculated reservoir pressure and **b** is the slope of the regression line plotted on a logarithmic scale. (This relationship is assumed to be logarithmic under ideal condition.)

Formation permeability, **K**, can be calculated from this relationship when other parameters are known. These parameters are used in a specific adaptation of Darcy's Law. In this analysis these parameters are as follows:

> The parameter 'Q' = the rate at which fluid flows from the porous formation into the borehole and into the drill pipe during the flow period of the test. This rate is normalized to bbl/day. The fluid recovered during a DST is generally reported in units of height (feet) within the drill string. Converting this to barrels requires knowing the internal diameter of the drill collars and how many feet of drill collars were run, and the internal diameter of the drill pipe.
>
> The parameter 'FVF' = formation volume factor which is a conversion factor for translating surface volume to reservoir conditions. Thus it is an estimate for the formation water or drilling fluid compressibility.
>
> The term 'b*ln(10)' allows for a conversion of b to its logarithm using base 10.
>
> The term 'Visc' = the viscosity of the produced fluid, in centipoises (cp). For pure water the Visc value = 1 cp.

Formation Transmissibility' = 162.6 * Q * FVF / b

The quantity 'Kh' = the permeability of the formation (K) multiplied by the number of feet of permeable formation) and equals the Formation Transmissibility * Visc

The permeability (K) is calculated by dividing the Kh by h where h is the net thickness interpreted by the geologist after examining the well logs

The DST data which were integrated into this project's flow model are summarized in the table below (Table 5.3).

Table 5.3: Useable Drill Stems Tests for the Artesia Fairway (San Andres formation)

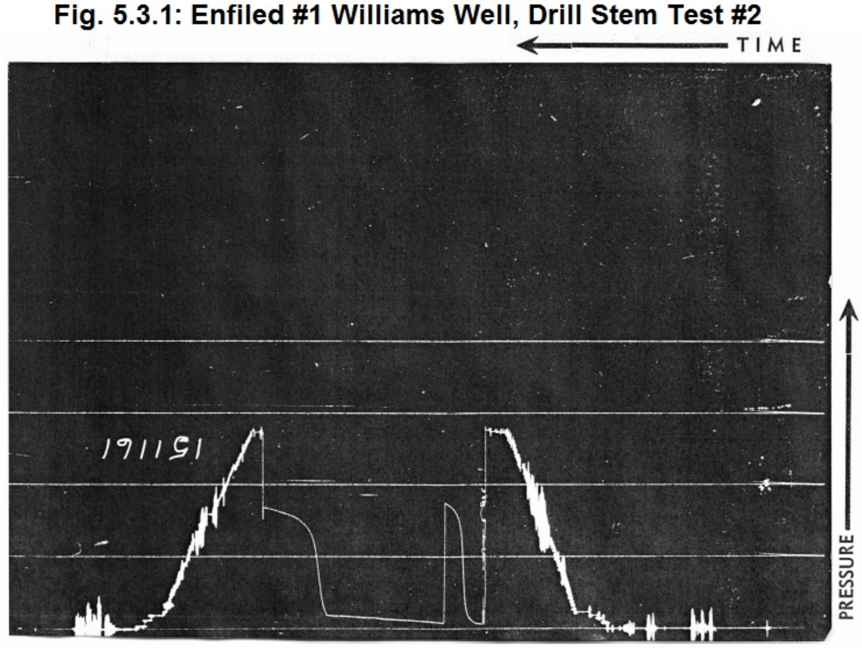
Well Name	County	Gauge Depth	Horner P	Q	FVF	b*ln(10)	μ	Transmblty	Kh	h	K	Poten Head
		ft bgs	psi	bb/day	bbl/bbl	psi/cycle	cP	mD∑ft/cP	mD∑ft	ft	mD	ft amsl
Amerind #1-16 St	Lea	5108	1756	21	1.04	1265	1	2.836	2.836	92	0.03	2618
Argee 31 Cantina Test #1	Lea	5491	2407	43	1.04	106	1	69.114	69.114	250	0.28	3636
Argee 31 Cantina Test #2	Lea	5497	2273	6	1.04	1881	1	0.570	0.570	132	0.00	3328
Siete #1 Yuma Federal	Lea	4775	1912	78	1.03	298	1	43.921	43.921	90	0.49	3337
Rand #1 Hopper	Lea	5347	1932	48	1.03	582	1	13.892	13.892	125	0.11	2653
Enfield #1 Williams Test #2	Lea	5163	1966	23	1.03	616	1	6.216	6.216	60	0.10	2921
Enfield #1 Williams Test #3	Lea	5426	2086	26	1.03	792	1	5.589	5.589	30	0.19	2928
SOHIO #1 Bordages	Lea	4515	1545	654	1.03	114	1	958.429	958.429	80	11.98	2544
Trainer #1 Sherrell	Lea	5089	1972	316	1.03	319	1	165.902	165.902	119	1.39	2586
Monsanto #1 Kincaid	Eddy	3768	1634	50	1.03	1125	1	7.407	7.407	96	0.08	3557
Forest #1 Harral	Pecos	2879	1149	2	1.00	295	1	1.276	1.276	39	0.03	3015
Estoril #1 Shell Mann	Pecos	1928	869	7	1.00	222	1	5.090	5.090	48	0.11	2263
Burk #1 Eaton	Pecos	3097	1533	15	1.03	363	1	6.829	6.829	82	0.08	2758
Abell #2A State Corrigan	Pecos	2369	1112	62	1.03	184	1	56.435	56.4350	12	4.70	2535
Abell #2B State Corrigan	Pecos	2383	1087	91	1.00	171	1	86.679	86.679	15	5.78	2466
Ram #5 Kramer	Pecos	2900	1427	18	1.00	444	1	6.58	6.580	49	0.13	2710

These 16 DSTs were the only tests drawn from the larger data set that successfully tested (and accurately represented) the stratigraphic interval of interest within the defined geographic fairway. The larger data set is tabulated in the appendix of this report.

An example of a DST chart recording is illustrated below. This chart in particular is from the Enfiled #1 Williams well, test #2:

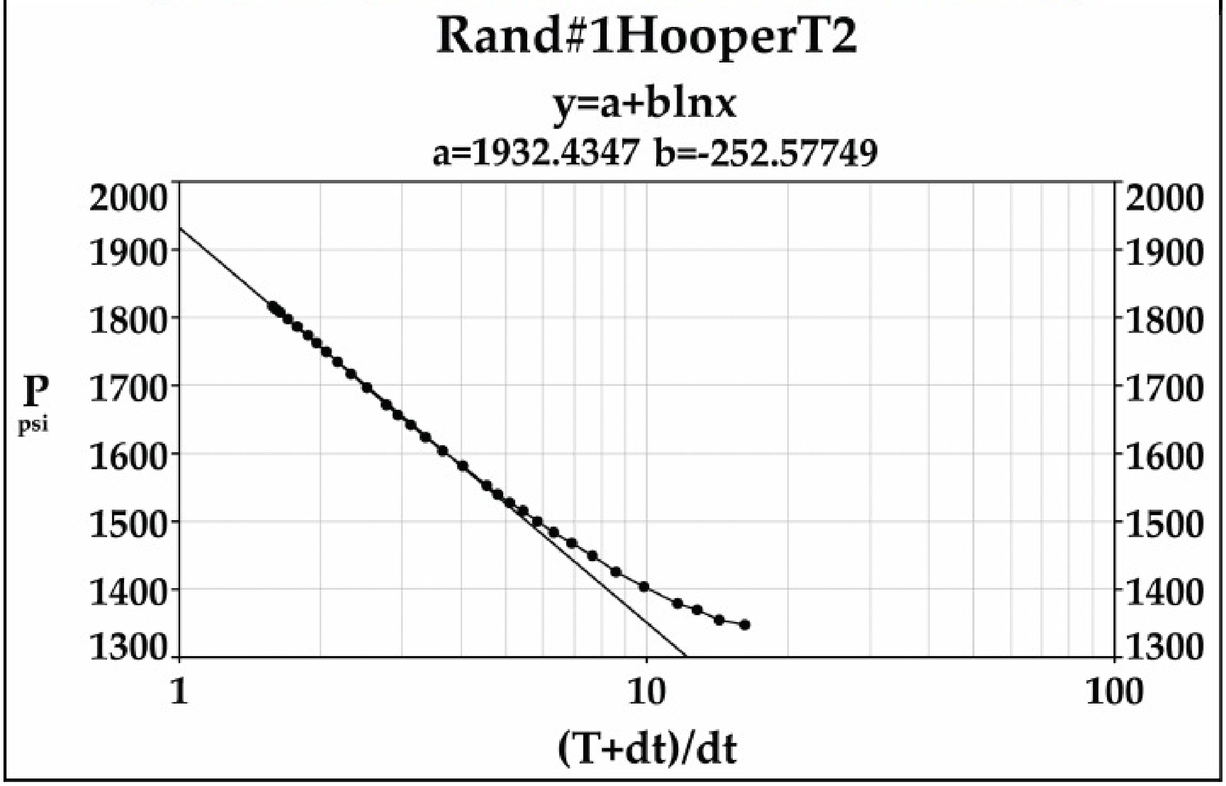
The elegant but somewhat hidden nature of the Horner relationship can be revealed by studying a few graphs of Pressure versus Horner Time data. Ideally we would expect that a perfect drill stem test would result in a straight-line plot of measured pressure against the log of Horner Time. However, borehole conditions usually cause a divergence from ideal conditions.

Fig. 5.3.1: Enfiled #1 Williams Well, Drill Stem Test #2



The Horner plot for test #2 in the Rand #1 Hooper well in Lea County (Fig. 5.3.2) illustrates borehole conditions which are near ideal. The data points at the beginning of the test (large values of Horner Time) are slightly above the straight-line plot. These values probably represent the supercharging of the formation with drilling fluid. The remainder of the test data conform with the expected relationship, and we can therefore conclude the extrapolated pressure at HT=1 (an infinitely long shut-in period) is highly reliable.

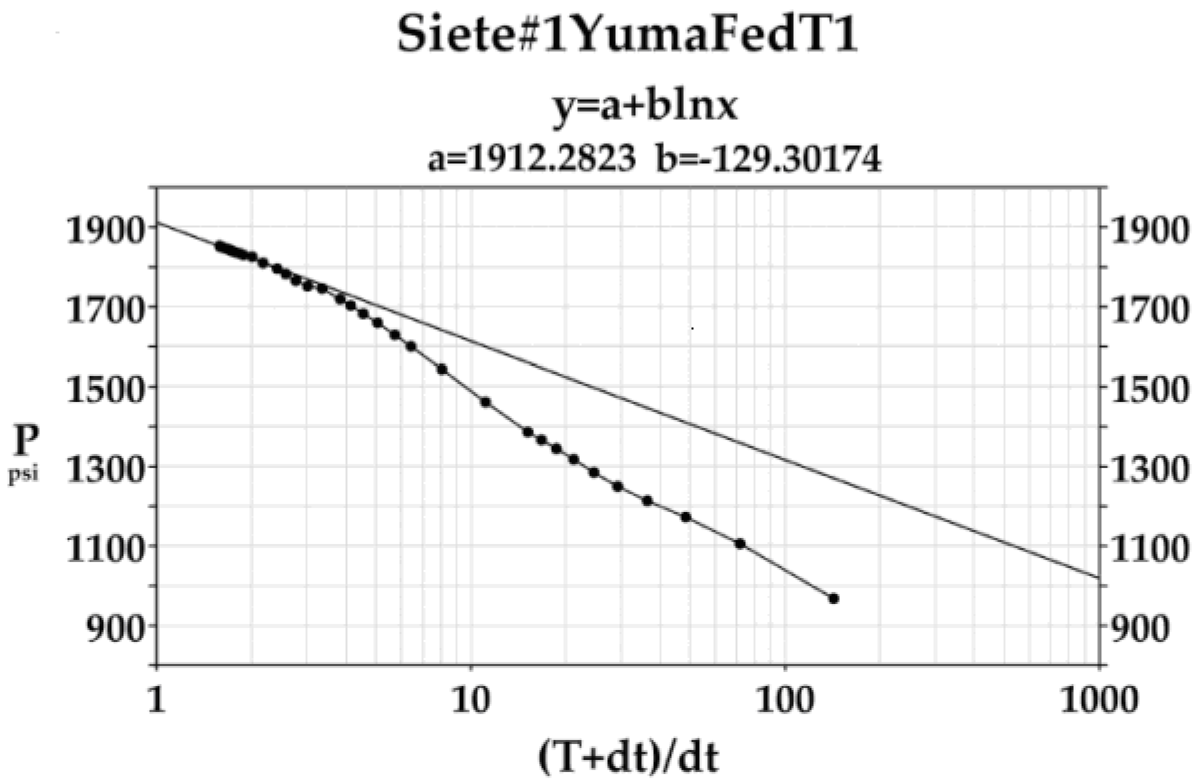
Fig. 5.3.2: Horner plot for test #2 in the Rand #1 Hooper well in Lea County



A somewhat different phenomenon is illustrated by the Horner plot for the DST in the Siete

#1 Yuma Federal well in Lea County (Figure 5.3.3). The pressure values at the beginning of the

Fig. 5.3.3: Horner Plot for the Siete #1 Yuma Federal Well (Test #1)



test are distributed below the regression line. These measurements were likely influenced by formation damage. Such damage is commonly caused by the invasion of drilling mud solids into the sidewall of the borehole, and the deposition of mud cake on the sidewall. Again at the end of the test the measurements conform reasonably well to the postulated relationship and we can assign a high degree of confidence in the extrapolated reservoir pressure.

Calculations from these data of the formation permeability can be executed with confidence only if the Horner relationship is valid. It would not be difficult to imagine formation damage severe enough, and supercharging large enough, that an extrapolated Horner pressure would be invalid.

6.0. FAIRWAY REFINEMENT/DELINEATION

The delineation and refinement of the trend was an effort by a number of participants in the study. Bob Trentham identified the outline of the two low permeability flanks that acted as boundaries to horizontal flow, and the central high permeability pathway. Arcadis provided regional maps with well control onto which the outlines were plotted. ROZ team members Phil Eager and Saswati Chakraborty gathered wells to populate the cross section network. They ensured that wells with DST, well pressure tests, water chemistry, core reports, and other data were included in the cross section network.

As previously discussed, structure maps, well logs, cross sections and exploration and production knowledge of the fairway were used to identify the high permeability portion of the trend where the meteoric derived sweep has effectively reduced the oil saturation to ROZ levels. Core reports were used to document the thickness, permeability ranges and average porosities of the high permeability portion of the trend. Precise locations (latitude and longitude), and block and section locations

In section 5.1.2 above the Faiway boundaries (horizontal) in map view were discussed and in section 5.1.2 the vertical units were identified including the major porous unit (judkin) allowing maximum flow of the Artesia Fairway. The details of hydrology of the Fairway are discussed in Section 7 and sub sections.

7.0 HYDRODYNAMIC MODEL DEVELOPMENT

The focus of the developed model is the Artesia Fairway of the San Andres Formation. The developments of ROZs from several San Andres oil fields using CO_2 EOR is currently underway and represents significant potential production from at least five major Permian Basin oil plays (Koperna et al., 2006). Though numerous fairways exist within the San Andres, the Artesia Fairway was the first fairway selected for groundwater modeling. The Artesia Fairway extends along the perimeter of the Delaware Basin in an arc-shaped pattern that follows the trends of the Northwest Shelf and Central Basin Platform (Fig. 7.1, Appendix A-2). The Artesia Fairway extends from the outcropping of the San Andres Formation in far western Eddy County, New Mexico to its terminus in eastern Pecos County, Texas. Counties within the study area include Eddy and Lea Counties in New Mexico and Ward, Winkler, and Pecos Counties in Texas. The lateral boundaries of the Artesia Fairway are defined by structural and porosity changes within the San Andres Formation. To the south and west, the San Andres transitions into low permeability formations within the Delaware Basin. The eastern boundary of the Artesia Fairway is marked by a zero porosity zone formed due to evaporite plugging within the San Andres.

7.1 Objectives and Scope

The objective of the study is to improve the understanding of the hydrogeologic flow regime within the Artesia Fairway of the San Andres Formation through the development of a numerical groundwater flow model. The model was developed to evaluate flow conditions during the geologic past when hydrocarbon flushing is thought to have occurred. The study also considers current flow conditions within the Artesia Fairway since observational measurements of the flow conditions are available for this time period that can be used to calibrate and verify the representativeness of the flow model. This calibration step is essential to insure that the modeling performed during geologic type is as accurate as possible. The calibration steps include the evaluation of modern groundwater conditions prior to any anthropogenic development in the region and after development associated with water and oil production. The scope of the study includes the necessary steps for the development of the groundwater flow model and consists of:

- compilation and review of the available regional data
- refinement of the regional hydrogeologic conceptual models for both the current flow system and the flow conditions during the geologic past
- groundwater flow model construction and calibration

- model simulations and analysis.
- parameter sensitivity analysis, and
- documentation.

The modeling evaluation provides insight into the current flow regime and differences with the conditions during the geologic past including flow rates, directions, sources of water, and discharge pathways. The evaluation identifies the factors that affect residual oil formation and evaluates the influence of uncertain geologic conditions. A description of the flow model development process and the results of the model evaluation are provided in the following sections.

7.2. Conceptual Site Model

The conceptual site model (CSM) is a generalized description of the geologic and hydrogeologic conditions of the study area. The CSM is based on review of all pertinent and available data and information, and serves as the basis for the development of the numerical groundwater flow model. Sources of available data include published literature, other geologic studies and information, and information from publically accessible databases including those maintained by Information Handling Services (IHS), PETRA (energy information, software, & solutions software), the U.S. Geological Survey (USGS), the Midland Energy Library, Railroad Commission of Texas, New Mexico Water and Infrastructure Data System (NM WAIDS), New Mexico Office of the State Engineer (NMOSE) – New Mexico Water Rights Reporting System (NMWRRS), GO-TECH Petroleum Web, and the Texas Water Development Board (TWDB). Data compiled from these databases include formation contact depths and elevations, drill stem test data, well completion details, water chemistry data, permeability and hydraulic conductivity data, and oil, gas, and water production data.

The following sections describe the geologic and hydrogeologic framework of the Permian Basin within western Texas and southeastern New Mexico, with a focus on the stratigraphic units that influence flow conditions within the San Andres Formation and the Artesia Fairway. This framework was used as the basis for the construction and development of the numerical groundwater flow model.

7.2.1. Geologic Framework

The discussion of the geologic framework describes the structural and depositional history of the Permian Basin that formed in the late Pennsylvanian and into the Permian period, with a focus on the stratigraphy and large-scale structural modification of the Guadalupian strata, development of regional groundwater flow paths (i.e. fairways) as well as the hydrodynamic formation of ROZs in the San Andres on the western side of the Central Basin Platform. Much of the information presented on the physiography and stratigraphy of the Permian basin is taken from Ward et al. (1986) unless otherwise noted.

7.2.1.1. Physiography and Stratigraphy of the Permian Basin

The Permian Basin covers approximately 115,000 square miles in western Texas and southeastern New Mexico. It initially formed as a broad, shallow asymmetric structural depression within the Precambrian basement at the southern portion of the North American continental plate. During the early and mid-Paleozoic, the Tobosa basin existed in roughly the same location as the later Permian Basin. The Tobosa Basin lacked the major physiographic features which are characteristic of the Permian Basin. Deposition occurred periodically with approximately 6,000 feet of shallow water shelf carbonates, sandstones, and shale sediments that were slowly deposited. Many parts of the early to mid-Paleozoic time period are not represented in the stratigraphic column due to erosion during the Sloss Sequence major sea level lowstands (Hills 1972).

In the late Paleozoic (early Mississippian and into the Pennsylvanian period), the North American and South American plates tectonically converged (Ouachita collision). A fold-thrust belt formed within the southern portion of the basin, resulting in uplift along the Marathon Thrust Belt and the development of the incipient Central Basin Platform, the Delaware, Val Verde, and Midland Basins, and the Ozona Arch. After plate convergence ceased, extensive deposition of carbonates and siliciclastics occurred and continued throughout the Permian. Black shales, silts, and carbonates were deposited in the central portions of the basins that formed on either side of the Central Basin Platform, broad carbonate ramp-like shelves began to form around the margin, and large-scale depositional channels formed at the north and south ends of the Central Basin Platform and between the Southern Shelf and the Apache Platform. In the latter part of the Permian, the basin was cut off from the ocean, and evaporites were deposited and filled in the basin. The large-scale features of the Permian Basin are shown in Figure 7.1 (Appendix A-2). These features include the Delaware and Midland Basins, the Central Basin Platform, the Northwest Shelf and Eastern Shelf, and the San Simon, Sheffield, and Hovey depositional channels.

Figure 7.2
PERMIAN BASIN STRATIGRAPHIC CHART

SYSTEM	SERIES	DELAWARE BASIN		CENTRAL BASIN PLATFORM		NORTHWEST SHELF			MIDLAND BASIN	
PERMIAN	OCHOA	Dewey Lake		Dewey Lake		Dewey Lake			Dewey Lake	
		Rustler		Rustler		Rustler			Rustler	
		Salado		Salado		Salado			Salado	
		Castile								
	GUADALUPE	Delaware Mtn. Group	Lamar		Tansill	Whitehorse	Tansill	CAPITAN	Whitehorse	Tansill
			Bell Canyon		Yates		Yates			Yates
					Seven Rivers		Seven Rivers			Seven Rivers
			Cherry Canyon		Queen		Queen			Queen
					Grayburg		Grayburg			Grayburg
			Brushy Canyon	Word	San Andres	Word	San Andres	GOAT SEEP	Word	San Andres
					Glorieta		Glorieta			San Angelo

Intense tectonism continued throughout the Pennsylvanian and into the early Permian period, and the broad carbonate shelf and margin ramp that initially formed during the Wolfcampian (early Permian) evolved into a rim around the edges of the Delaware and Midland Basins. In the early Leonardian (middle Permian), the shelf developed a series of barriers along the seaward edge, becoming much more distinctly rimmed. Continued local tectonism resulted in complex depositional patterns around the rim. During this time, siliciclastic deposition predominated within the Delaware Basin, and carbonate deposition predominated on the platform and shelves. By the late Guadalupian (late Permian), carbonate accumulation was restricted and siliciclastic deposits of sandstone, siltstone, halite, and anhydrite were cyclically deposited on the shelves. These shelf and basin deposits are referred to as the Guadalupian Series.

Figure 7.2 shows a generalized stratigraphic column for the Upper Permian aged sediments within the Permian Basin. The Permian aged strata are divided into four series, from lower to upper — the Wolfcampian, Leonardian, Guadalupian and Ochoan. The lowermost, Wolfcampian and Leonardian are not shown in Fig. 1.1, but would immediately underlie those shown. The Guadalupian, including the San Andres formation, dominates the production in the Permian Basin and was the interval of interest for the study. These sedimentary rocks are a typical example of the facies observed in carbonate dominated shelf environments, which generally consist of three main depositional features: deep water basin materials; carbonate shelf margin reef materials, back-reef shelf lagoons, and coastal playas and flats. Outcrops of these strata have been observed in the Guadalupe Mountains (complete sequence), the Delaware Mountains, and the Apache Mountains (Hill, 1996). The Artesia Group is Equivalent to the Whitehorse Group in Figure 7.2.

The following sections describe the stratigraphy of the three main Guadalupian facies as seen in outcrops (Ward et al., 1986). Figure 7.3 (Appendix A-2) shows the Permian basin with the current extents of the each of the Guadalupian facies types (basin, reef, and shelf) including the Capitan Reef complex and the San Andres and Artesia Group Formations that occur as shelf deposits as described below. Figure 7.3 (Appendix A-2) also shows four cross section locations. Figure 7.4 (Appendix A-2) presents a northwest to southeast cross section in Eddy County; Figures 7.5 through 7.7 (Appendix A-2) present west to east across Lea County in New Mexico, and Ward and Pecos Counties in Texas, respectively. These sections show the general correlation between the various Guadalupian formations.

Basinal Facies – Delaware Mountain Group

The Basinal facies of the Guadalupian include the Delaware Mountain Group formations, which consist of interbedded gray limestones and thick, finely laminated clastic sedimentary rocks (Brushy Canyon, Cherry Canyon, and Bell Canyon Formations). These units are shown at the base of the cross sections in Figures 7.4, 7.5, and 7.7 (Appendix A-2), and are up to 4,000 feet thick towards the center of the Delaware Basin.

The limestones were developed from the shelf margin and are thickest on the edges of the basin, where deposition occurred as high energy shelf or shelf margin slumps or as organic rich limestone which can be correlated basin-wide. These channel fills include various facies such as fine-grained conglomerates, carbonate breccias, oolitic grainstones, wavy and laminated wackestones, and thin bedded siliciclastics. Fossils are rare in these limestones and where they do occur, they are silicified by chert. Locally, these limestones serve as significant seals above hydrocarbon-rich siliciclastic intervals. The limestones pinch out towards the central portions of the basin and are generally even or regular and laminated.

The clastics consist of siltstones and calcite-cemented, fine-grained sandstones, and are thinner at the margins with irregular bedding throughout. The siltstone is blanket-like and continuous, suggesting deposition from suspension. The sandstones are fine-grained, moderately to well sorted, poorly cemented and are generally confined to channels, as they were deposited by density currents.

Shelf-Margin (Reef) Facies

The Goat Seep and Capitan Formations are shelf-margin reef deposits that are located along a 300 mile long, relatively narrow belt that borders the Delaware basin and Northwest shelf areas (Figure 7.3, Appendix A-2)). The Goat Seep Formation is positioned on the Grayburg shelf edge. It is responsible for "closing off" the Sheffield Channel at the southern end of the Central Basin Platform. As the San Andres was essentially a distally steepened ramp, the San Andres is separated from the Goat Seep Formation and hence the Capitan Formation above in most areas. Other reef deposits consist of approximately 1,500 to 2,000 feet of massive dolomite and limestones overlying steeply dipping, thickly bedded blocky debris of the fore-reef facies. The relationship of the reef facies with the Basinal deposits is transitional, as the reefs were deposited at a break along the shelf. A steep slope exists within the upper portions of the Capitan formation (35 degrees and 25-30 degrees, respectively), with gentler bedding occurring toward the central portion of the basin, as shown in the Winkler County cross section (Figure 7.6, Appendix A-2). The Capitan reef core consists of calcareous sponges, encrusting algae such as stromatolites, and limey mudstones. The reef core represents approximately 10 percent of the volume of the reef. Reef talus and associated facies represent the other 90 percent. In the back-reef barrier area, a narrow belt of interbedded thin limestone and dolomite exists, as grainstones with small intraclasts and fossils (Texas Water Development Board, 2001).

Shelf Facies

Shelf facies of the Guadalupian series consist of widespread sheets or lenses of carbonates. These carbonates interfinger with the barrier reef facies on the down dip sections, but sharply contact updip evaporates, siltstones, and dolomites. These strata have strong vertical stratification as a result of high frequency sea level cycles during the early to mid-Guadalupian (Kerans et al., 1994). Subsidence of the Delaware Basin accelerated during the Guadalupian, which resulted in growth within the patch reefs and shoals as well as sediment deposition close to the shore. Sediments deposited during this period have become the cherty dolomites of the San Andres Formation. The San Andres Formation consists of a cyclic sequence of shallow water carbonates and evaporites that prograded across the shelf toward the Delaware and Midland Basins. Specific sequences include subtidal marine limestone overlain by smaller scale dolomite-anhydrite cycles, with caps of supratidal anhydrite, dolomite, and salt deposits at the extreme up dip end of the Northwest Shelf (Cowan and Harris, 1986). Two intervals of the San Andres have been identified based on the presence of a siltstone marker bed. The lower San Andres consists of the shoaling open-marine shelf limestone and dolomite with chert deposits, and the upper part of the San Andres is a thick sequence of the shelf and tidal-flat dolomite and anhydrite deposits (Cowan and Harris, 1986).

Above the San Andres lies the Artesia Group, which includes, from youngest to oldest, the Tansill, Yates, Seven Rivers, Queen, and Grayburg Formations. These formations consist of cyclic deposits of carbonates, clastics, and evaporites and gradually grade into either the Capitan Reef Complex (Tansill, Yates, and Seven Rivers) or Goat Seep Reef Complex (Queen and Grayburg) (Hiss 1975; Texas Water Development Board 2009). The Grayburg, which is the basal formation of the Artesia Group overlying the San Andres Formation, consists of interbedded dolomite with thin layers of fine-grained sandstone approximately 300 to 400 feet thick (Hiss, 1975). The Queen Formation is more clastic and evaporite rich than the Grayburg with a thick sandstone layer at the top that includes thin interbeds of shale and dolomite. The Seven Rivers Formation, consisting of a thinly bedded dolomite and evaporites with minor sandstones, gradually grades basinward into the Capitan Reef Complex.

The cross sections show the transitional contacts between the San Andreas formation and both the reef facies (Capitan Reef Complex) and the basin deposits of the Delaware Mountain Group, such as the sandstone of the Cherry Canyon formation in Figures 7.4 and 7.7 (Appendix A-2).

7.2.1.2. Structural Adjustment of the Delaware Basin in the Geologic Past and Hydrodynamic Formation of the Artesia Fairway

After the Permian Basin subsidence slowed, the Hovey Channel closed. The connection to the open Permian Ocean was cut off and the basin with normal salinities became an evaporitic interior drainage basin. More than 1,500 feet of anhydrite with minor carbonates covered the youngest members of the Artesia Group and Capitan Reef Complex. These were later covered by late Permian evaporates and Mesozoic sediments and the Guadalupian formations became deeply buried in the subsurface. Burial and the resulting increased temperatures resulted in the generation of and subsequent transport of hydrocarbons. For lower Paleozoic rocks, hydrocarbon generation may have occurred as early as the middle Ordovician. However, maximum generation of hydrocarbons in both the Permian and older formation likely occurred by the end of the Permian and through the Triassic (Hill, 1996).

By the late Mesozoic Era, deposition over much of the basin ceased, and in the late Cretaceous, the Laramide Orogeny began. This orogeny resulted in several thousand feet of uplift within the Guadalupian rocks west of the present-day Delaware basin (Lee and Williams, 2000). Laramide deformation continued on into the early Tertiary period of the Cenozoic, and the basin tilted eastward. A period of igneous activity occurred in the southern Delaware Basin during the Oligocene, and the igneous intrusions along with lithospheric thinning heated the Permian sediments. A second phase of hydrocarbon generation and migration likely occurred during this period (Trentham, 2011a).

In the late Oligocene to early Miocene, Basin and Range extension became dominant and the western part of the basin was further uplifted. Tilting and extension of the eastern limb of the Rio Grande Rift occurred, including the Guadalupian formations of the Delaware Basin. Hydrogen sulfide was produced from reactions of hydrocarbons with sulfate-bearing evaporites, and thermal caves developed in the recently uplifted Guadalupe Mountains in the north, and in the Glass Mountains in the south (Hill, 2000).

The Tertiary uplifts first induced strong hydraulic gradients in the Guadalupian strata. This changed the hydrodynamics within the Permian Basin as massive volumes of meteoric-derived water from an area approximately half that of the basin itself recharged the basin from west to the east through the newly-exposed San Andres and other Guadalupian strata (Lindsay, 1998). Recharging water is theorized to have partially or completely reduced oil columns to residual oil saturation as hydrocarbons migrated towards the exit points. As the classic horst and graben extensional faulting of the Basin and Range province developed in the middle to late Miocene, meteoric recharge was significantly reduced when only small land masses in the Guadalupe and Sacramento Mountain areas were available for recharge.

The Artesia Fairway is a flow zone or stratigraphic bound interval within the interconnected, permeable portions of the San Andres prograding facies that developed on the northern and eastern side of the Delaware Basin as a proximal shelf deposit. The Artesia Fairway extends along the north and east side of the Delaware Basin on west side of the Central Basin Platform, as shown in Figure 7.8 (Appendix A-2). When the uplift and subsequent low-flow recharge from the exposed mountain ranges occurred, the water followed permeable pathways within the San Andres located along the eastern and western margins of the Central Basin Platform, the Northwest Shelf, and in other areas to the northeast (Figures 7.3 and 7.8, Appendix A-2). The San Andres reservoirs therefore developed as regional aquifer systems within the established permeability zones. Porosity within the San Andreas pinches out updip toward the interior of the Central Basin Platform and Northwest Shelf. This zero porosity zone formed due to evaporite plugging and marks the eastern and northern boundary of the Artesia Fairway (Figure 7.8, Appendix A-2).

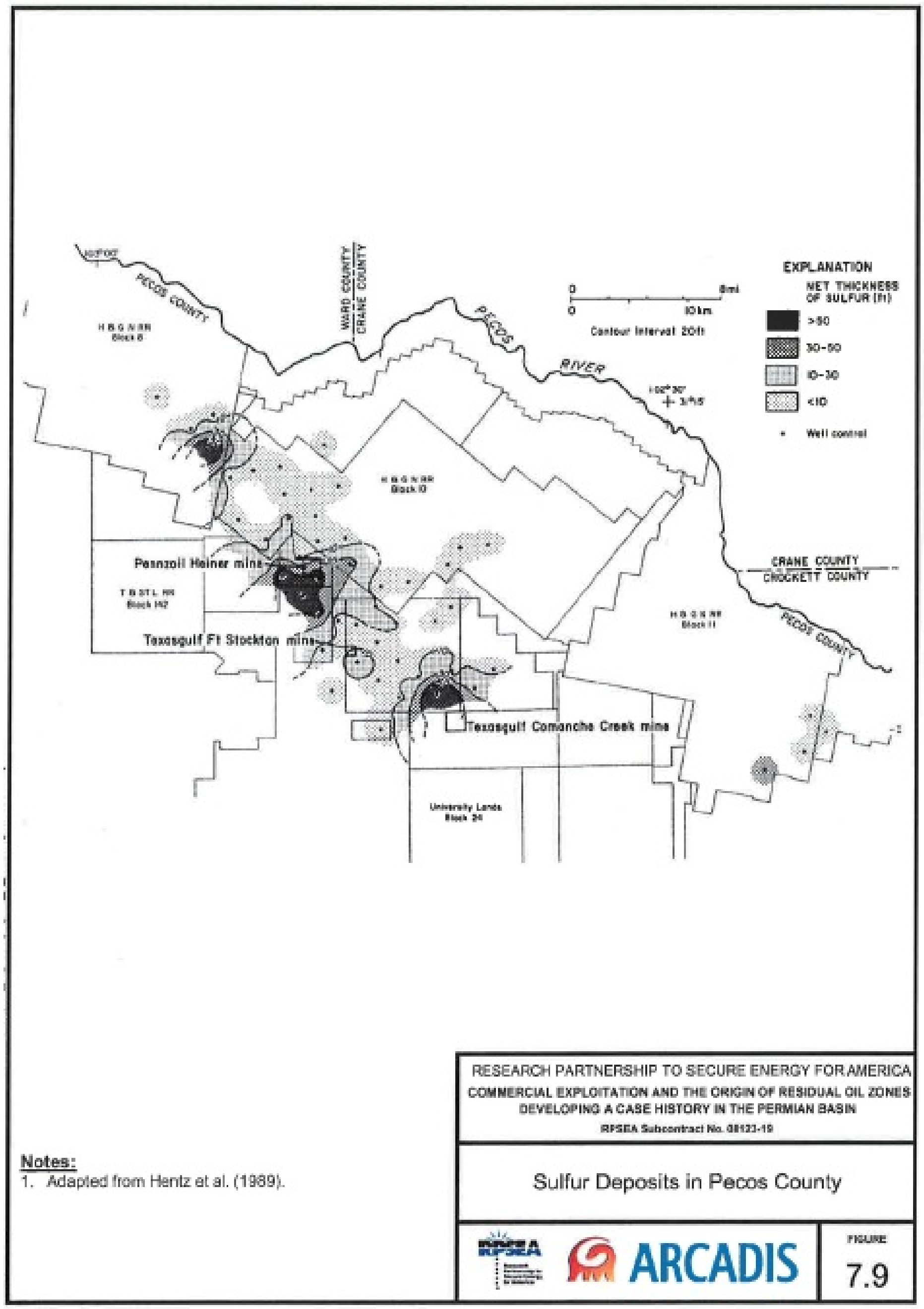
Because of the structural and hydrodynamic changes that occurred during tectonism, high volume recharge, and the horst and graben formation, the flow zones within the San Andres are different than the zones through which hydrocarbons or oil had originally migrated. Groundwater movement has caused oil/water contacts to tilt in the direction of flow, which provides additional evidence for flow along regionally-established fairways, as well as indications of the potential for ROZs to occur.

7.2.1.3. Residual Oil Zones Within the Upper Carbonates of the Permian Basin

The origin and distribution of ROZs is now only beginning to be understood. However, some conceptual models exist that are based on what is known about hydrocarbon migration and distribution, as well as the hydrodynamic changes in the basin resulting from tectonism and subsequent horst and graben formation. Thick intervals of immobile oil at or near residual saturation are common in Guadalupian strata and are found where no hydrocarbon entrapment is observed and well beyond the footprint of producing oil fields. Static reservoir modeling has been used to explain these residual oil zones as transition zones even when evidence of hydrodynamic displacement is clearly present. All oil reservoirs have an interval below the oil-water contact where the oil saturation decreases rapidly with depth (transition zones). The thickness of this interval is controlled by capillary forces and as a function of fluid dynamics, as rocks with thicker zones developing when rocks are oil-wet as opposed to those with pores that are water-wet (Melzer, 2006).

ROZs include the transition zones but also include residual oil within intervals that have been subjected to hydrodynamic displacement processes and exist at thicknesses much greater than what would be attributed to normal capillary effects. The hydrodynamic processes for ROZ formation can be described as either regional or local basin tilt, breached and reformed seals, or altered hydrodynamic flow fields (Melzer, 2006). These processes have been described as “Mother Nature’s Waterflood“ that occurs after an initial accumulation of oil in the subsurface trap. For a more detailed description of ROZ types, see Melzer et.al. (2006).

This study focuses on ROZs developed from altered hydrodynamic conditions within the aquifers of an oil-rich basin (ROZ Type 3 described above). Hydrocarbon migration pathways in the Permian Basin are well documented and generally occurred as basin to shelf migration from the late Permian through late Cretaceous. The hydrocarbons in the San Andres formation became trapped at the shelf due to the loss of porosity and permeability from infilling by evaporites, and sealed above and below by relatively impermeable evaporite and other carbonate deposits. During the Laramide orogeny, the hydrocarbons remained in place; mobilization did not occur until the Rio Grande Rift was uplifted during the Basin and Range tectonism. At this time, the significant volume of meteoric derived water that recharged the basin flushed through the permeable portions of the Guadalupian strata and the hydrocarbon traps southeastward along regional aquifer pathways such as the Artesia Fairway.



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RPSEA Subcontract No. 08123-19

Sulfur Deposits in Pecos County

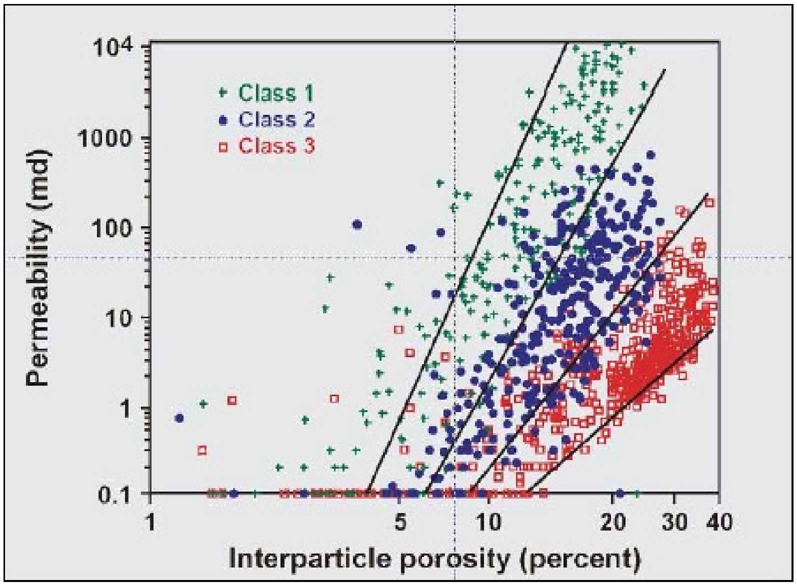
FIGURE 7.9

Notes:
1. Adapted from Hentz et al. (1989).

When the meteoric recharge was reduced during the creation of the horst and graben, a portion of the oil was able to migrate back into the crest of some structures along the fairways (Trentham, 2011a) and new oil/water contacts formed above the original accumulations with tilts controlled by the new hydrodynamic gradients (Brown, 2001). The remaining oil migrated along the fairways to exit points, or remained as residual oil in the down dip basin and shelf edge rocks. Some of the traps were left with residual oil saturations. ROZ intervals of approximately 200 to 300 feet have been found beneath the oil/water contacts of Guadalupian strata. Tilted oil-water contacts, distributions of dissolved solids or salinity, the presence of "sour" hydrocarbons, and geological settings conducive to lateral aquifer flow such as those that occurred in the Permian Basin that formed the Artesia Fairway are all indicators of the presence of ROZs. Tilted oil/water contacts have been identified in San Andres oil fields across the Northwest Shelf with tilt directions that are indicative of the modern hydrodynamic gradients and flow directions (Brown, 2001).

7.2.1.4 Sulfur Deposition in Pecos County

Major sulfur deposits located in Pecos County are thought to be evidence of a significant exit pathway for oil and water migrating along the Artesia Fairway. As the meteoric water that recharged the Guadalupian strata during the late Oligocene and early Miocene tectonism passed through anhydrite-rich carbonate aquifers, sulfate-reducing anaerobic bacteria caused



Source: "Rock-Frabric, Petrophysical Classification for Carbonate Rocks", Presentation by F.Gerry Lucia, Reservoir Characterization Research Laboratory Bureau of Economic Geology The University of Texas at Austin

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Limestone Rock Fabric Relationships

RPSEA ARCADIS FIGURE 7.11

enrichment in reduced sulfurous compounds. The generation of the sulfur and its host limestone is considered to be epigenetic and to have formed biogenetically within a calcium sulfate environment (McNeal and Hemenway, 1972).

The Fort Stockton Sulfur district is a series of large sulfur deposits found in northern Pecos County at the crest of the regional anticline formed at the edge of the Delaware Basin (Figure 7.9). The mines occur within the porous limestone facies in the evaporitic Salado Formation of late Permian, which overlies the San Andres Formation of the early Permian. These mines are believed to represent exit pathways on the Central Basin Platform for the flushed oil and meteoric waters that flowed through the Artesia Fairway. Thickness maps of sulfur ore bodies suggest the presence of at least nine discharge points through which groundwater flow occurred. Sulfur mines were located at three of these locations as noted in Figure 7.9. Based on TDS values of groundwater in the Rustler, vertical discharge may have taken place up to the Rustler where lateral migration to the east and out of the Fairway could have occurred (Jones et al., 2011).

7.2.1.5. Upper San Andres Formation Characteristics

The San Andres is a basinward-dipping shelf carbonate formation found throughout most of New Mexico and west Texas. This formation grades updip into siltstones, evaporites, and dolomites deposited in the playa and lagoon shelf areas. The San Andres consists of an upper non-cherty dolomite and a lower cherty limestone member. Total thickness of the San Andres Formation is 700 to 1,600 feet (Texas Water Development Board 2009). On the Delaware Basin margin, the San Andres Formation transition from shelf carbonate to reef environments is approximately 3 miles wide and trends parallel to the Capitan Reef front (Hiss, 1975). In the reef margin, the San Andres Formation is separated from the Grayburg by the anhydrite rich upper San Andres on the Central Basin Platform. It is separated from the Grayburg on the

Northwest Shelf by the Premier Sandstone. As mentioned above, the Goat Seep Formation is nested in the upper Grayburg margin and in most areas, is separated from the Capitan Formation by the presence of relatively impermeable silts, tight dolomites and evaporates.

Although two intervals of the San Andres have been identified based on the presence of a siltstone marker bed, in terms of unit porosity and permeability, this unit can be further delineated. Within the upper and "middle" portion of the San Andres, a zone of higher porosity and permeability approximately 200 to 300 feet thick has been identified in drill cores and wireline logs taken throughout the Artesia Fairway on the western side of the Central Basin Platform. This portion of the San Andres is the focus of the current modeling effort as this is the interval through which much of the meteoric water and oil are thought to have been flushed and where ROZs are likely to occur. An Isopach map of the porosity zone of the San Andres is presented as Figure 7.10 (Appendix A-2). The base of the modeled San Andres porosity zone is the Brush Canyon Bypass surface.

The shelf dolomites and grainstones generally have higher porosities than the basinal strata. The porosity within the San Andres is secondary as a result of dissolution of shells and other marine life (moldic porosity), primary interparticle porosity in the dolomitized San Andres, and primary interparticle porosity in the siltstones. This porosity generally ranges from 7 to 15 percent (Ward et al., 1986). Some areas within the San Andres dolomites have reduced porosity that has been sealed due to plugging by evaporites. A "zero porosity" line in the Central Basin Platform marks the eastern boundary of the Artesia Fairway. On the Northwest Shelf portion of the Fairway, the same loss of porosity in the porous dolomites of the San Andres occurs 4 to 5 miles northward of the shelf.

Porosity and permeability in dolomites are generally well correlated. Figure 7.11 presents a plot that shows permeability as a function of porosity for three rock-fabric or interparticle porosity types. These textural classifications are based on the relative degree of mud or grains within the rock as well as on the degree of binding between the particles during deposition. Of the three classes shown, the San Andres petrophysical properties are more reflective of Class 1 and 2, with permeability in the range of 1 to 10 millidarcy (md) for the general values of porosity within the San Andres.

7.2.2 Hydrogeologic Framework

Hydrodynamic flow through the San Andres Artesia Fairway is influenced by the larger flow regime within the Guadalupian formations of the Permian Basin. Flow through individual formations within the Guadalupian series is controlled by the hydraulic properties of the formations, the imposed hydraulic gradients, and their physical dimensions (thickness and lateral extent). Hydrodynamic flow is concentrated in formations that have physical properties favoring the greater transmission of fluids as characterized by the permeability, hydraulic conductivity, porosity, and transmissivity of the formations, and flow through the system as a whole is controlled by the relative positioning of formations with differing hydraulic properties. Hydraulic head gradients imposed on the system provide the driving force that moves water through the system. The head gradients are influenced by the hydraulic properties of the formation, but also by the relative position of a location to areas of recharge and discharge, which can be both naturally occurring or caused by human activity (e.g. extraction from wells).

Hydrodynamic flow through the Guadalupian formations has changed over time. Since deposition of the Guadalupian formations in the Permian, the flow system has been continually adjusting in response to shallow to deep burial and associated diagenetic overprints which resulted in a second dolomitization event and dissolution of evaporates, various tectonic uplifts, rifting, sea level changes, and climate fluctuations. In addition to adjustments induced by changing geologic conditions and climatic conditions, the flow system has been dramatically altered by in the last century by human activity related to agriculture, public water use, and oil and gas production.

This section of the study focuses of three time periods with distinct hydrodynamic flow regimes, which are hereafter designated the as pre-development period, the post-development period, and the geologic past. The post-development period is defined as beginning in the middle 1920s when wide scale commercial production of oil and gas began in the Delaware Basin and continuing until the present. This period reflects a time when the flow regime in the Delaware Basin began to be dramatically altered by large-scale groundwater extraction. The pre-development period is defined as occurring prior to middle 1920s when groundwater extraction was presumed to be relatively small (with some exceptions). The pre-development period is assumed to be representative of the entire span of human history up until middle 1920s. The geologic past is defined as being far back into pre-history or into "deep time". The geologic past considers time periods of hundreds of thousands to millions of years over which significant changes in regional tectonics occurs. The geologic past primarily considers the latter half of the Cenozoic Era over which the majority of hydrodynamic flow is thought to have occurred, but is influenced by the entire geologic history of the region. Though the purpose of this study is to evaluate flow conditions in the geologic past, pre-development and post-development flow conditions are also important since observational data are available for these time periods which provide a basis for conceptualizing conditions during the geologic past. Specific geologic periods considered are described in the following sections.

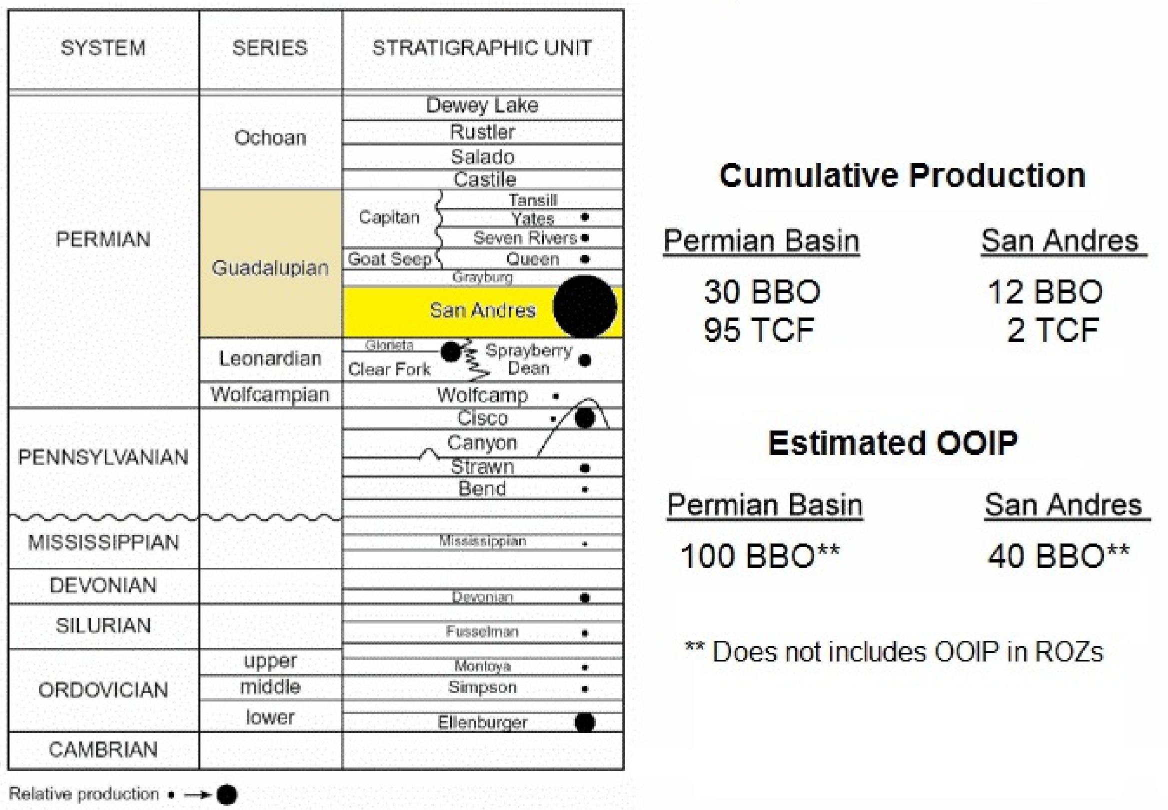
7.2.2.1. Hydrogeologic Units

The Guadalupian formations were grouped together based on similarity of their physical properties to allow for a clearer understanding of the flow regime through the system. The formations were grouped according to relative permeability, which is a measure of the relative ability of the formation to transmit fluid. The Guadalupian formations can be divided into three general categories based on the relative differences between the permeabilities of the formations, which also correspond to the three depositional facies of the Permian formations in the Delaware Basin. These are designated as basin aquifers (basinal facies), shelf aquifers (shelf facies), and shelf-margin aquifers (shelf-margin facies). The stratigraphy is illustrated in Figure 7.12.

Basin Aquifers

The basin aquifers within the study area include the Guadalupian formations present within the Delaware Basin (Figure 7.3, Appendix A-2) and include the interbedded sandstones, shales, and limestones of the Bell Canyon, Cherry Canyon, and Brushy Canyon Formations (Delaware Mountain Group). Saturated strata within the Delaware Mountain Group are capable of transmitting some quantity of water, but most of the units have very low permeabilities and function as confining units (both laterally and vertically). Locally higher permeabilities likely occur, such as in isolated sandstone channels in the Bell Canyon Formation (Beauheim and Holt, 1990), but the group as a whole can be considered as a single unit with very low permeability. Although the Delaware Mountain Group grades laterally into and inter-tongues with the shelf and shelf margin aquifers, it likely contributes very little flow to these aquifers.

Fig. 7.12: Permian Basin Stratigraphic Chart with Cum Production and Estimated Original Oil in Place by Formation



Shelf Margin Aquifer

The shelf margin aquifers consist of the narrow belt of carbonate reefs, banks, and talus slopes that surround the Delaware Basin (Figure 7.3, Appendix A-2), and cross sections shown in Figures 7.4 through 7.7 (Appendix A-2). The shelf margin aquifers include the Capitan Formation and the Goat Seep Formation, but also locally includes the hydraulically connected back reef Carlsbad group (Tansil, Yates, and Seven Rivers formations) in the Guadalupe Mountains and the equivalent Vidrio and Tessey formations in the Glass Mountains (Standen at al., 2009). These units combined are typically considered a single hydrogeologic unit referred to as the Capitan Reef Complex; however, the Goat Seep Formation is not in hydraulic communication with the Capitan Formation in the shallower section in most areas. The reef complex forms an unbroken, continuous, arcuate aquifer on the northern and eastern edge of the Delaware basin extending from the Guadalupe Mountains to the Glass Mountains. To the west of the Guadalupe Mountains, down-faulting associated with the formation of the Salt Basin has disconnected the Capitan Reef Complex on the western side of the Delaware Basin from the remainder of the reef complex on the northern and eastern sides of the basin. In a small area on the southern edge of the basin and between the Glass Mountains and the Davis Mountains, the reef complex is not well developed and formed a sill across which normal sea water was able to circulate between the Delaware Basin and the open Permian Ocean. A narrow outlet from the Delaware Basin (Hovey Channel) exists in the area, which likely supplied seawater to basin until it became closed during the time of the deposition of the Tansill Formation (Standen et al., 2009).

The lateral contact between the Capitan Reef Complex with the fore-reef basin aquifers is typically distinct and sharp. However, the contact with the back-reef shelf aquifers is typically gradational and inter-tonguing such that the contact between the two is sometimes difficult to distinguish. Where the contact is not distinguishable, the Capitan Reef Complex may include carbonate banks developed in the back-reef shelf aquifers including those above the San Andres Formation (Hiss, 1975).

The Capitan Reef Complex is continuous, but is incised by numerous submarine canyons that trend roughly perpendicular to the complex (Figure 7.13, Appendix A-2). The canyons represent a series of stacked channels where clastic sediments were transported and deposited through topographic depressions in the reef complex into the Delaware Basin (Hill, 1996). The submarine canyons are incised as much as a thousand feet deep into the reef complex and are filled with sediments that have permeabilities that are several orders of magnitude lower than reef complex (Hill, 1996). Fracture systems generated by strain from syndepositional deformation may provide some permeable pathways through these canyons (Hunt et al., 2002). The submarine canyons locally reduce the thickness and transmissivity of reef complex and restrict flow relative to the thicker portions of the complex (Hiss, 1975). While submarine canyons are known to occur along the entire length of the reef complex between the Guadalupe Mountains and Glass Mountains, they are more numerous and deeply incised along the northern limb of the complex in Eddy and Lea Counties. Therefore, the restriction of flow through the reef complex is primarily observable along the northern limb of the reef complex (Hiss, 1975).

The carbonate reefs, banks, and talus slopes of the Capitan Reef Complex have high permeabilities, which are much higher than the adjacent basin and shelf aquifers. Over much of the reef complex, permeabilities may be two orders of magnitude greater than for the basin aquifers. Permeabilities in the reef complex are even larger in the vicinity of the Guadalupe and Glass Mountains where extensive networks of caves, caverns, and karstic porosity have developed. Permeabilities in these regions may be several orders-of-magnitude greater the rest of the reef complex (Hiss, 1975).

Shelf Aquifers

The shelf aquifers of the eastern Delaware Basin include the Guadalupian formations of the Northwestern Shelf, Central Basin Platform, and Southern Shelf and include the San Andres Formation and the Artesia Group. Note: the Artesia group is not shown on the stratigraphic column and should be added. The permeabilities of the shelf aquifers are variable, but tend to range from being similar to the permeabilities of the basin aquifers to being approximately and order of magnitude less than the permeability of the Capitan Reef Complex (Hiss, 1975).

The Artesia group formations are the back reef equivalents of the Capitan Reef Complex. The contact between the Artesia group and the reef complex is gradational and is difficult to discern in some areas. The Artesia Group formations are generally carbonate near the reef complex and grade into evaporitic sequences in the back shelf to sabkha transition. In most areas, the Artesia group has relatively low permeability and behaves more as a confining unit rather than an aquifer. The main exception is to west of the Pecos River near its outcropping where enhanced dissolution may locally increase the permeability of Artesia Group formations.

Though the San Andres is stratigraphically older than the Capitan Reef Complex, the upper portion of the formation may locally be part of the base of the back-reef boundary (Standen et al., 2009). The lower portion of the formation inter-tongues with the low permeability formations of the Delaware Mountain Group down dip. In most areas, the permeability of the San Andres limestone is relatively low and within the same range as the Artesia Group (Hiss, 1975). However, as discussed in Section 7.2.1.2, permeabilities are variable and narrow but lengthy facies tracts of increased permeability (fairways) exist within the San Andres. The Artesia Fairway is developed along the northern and eastern edge of the Delaware Basin and trends roughly parallel to the Capitan Reef Complex (Figure 7.8, Appendix A-2)). The Artesia Fairway is a permeability channel in the Judkins unit of the San Andreas Formation not to be confused with the Artesia Group.

In addition to the general permeability enhancement associated with the Artesia Fairway trend, other areas of enhanced permeability exist within the San Andres Formation. Similar to the Artesia Group, permeabilities within the San Andres Formation are locally greatly increased to the west of the Pecos River in the Roswell Basin near its outcropping in the Guadalupe and Sacramento Mountains (Summers, 1972). The "Artesian Aquifer" of the Roswell Basin occurs predominantly within the upper portion of the eroded San Andres Limestone (also extends into the lower Grayburg over portions of the basin) and is major source of water for the basin (DBSA, 1995). Permeabilities within the San Andres in this region may be several orders of magnitude greater than the majority of the formation in the subsurface (Summers, 1972). Areas of enhanced permeability have also been identified in southeastern Lea County and in northern Pecos County on the northern and southern end of the Central Basin Platform where elongate, high energy, grain-rich shoals, carbonate banks, and reefs have been described within the San Andres (Hiss, 1975).

Summary of Hydrogeologic Units

Excluding areas near outcroppings in the Guadalupe, Sacramento, and Glass Mountains where permeabilities may be greatly enhanced, the Guadalupian formations surrounding the Delaware Basin can be divided according to permeability as follows:

- Low permeability basin aquifers
- High permeability shelf margin aquifer (Capitan Reef Complex)
- Variable permeability shelf aquifers

The permeabilities of these groups differ by several orders of magnitude such that flow will largely be restricted to the high permeability units. In the vicinity of the Delaware Basin, these include Capitan Reef Complex and the more permeable zones and trends within the shelf aquifers, which are generally limited to fairways within the San Andres Formation. Only minor amounts of flow will occur through the basin aquifers and the widespread lower permeability zones within the shelf aquifers.

7.2.2.2. Hydraulic Properties

Extensive core data and logs are available from the numerous oil and gas fields within the Guadalupian Formations that have been used to characterize the hydraulic properties of the formations. These are supplemented by pumping tests and specific specific capacity tests from irrigation, public supply, and water flood supply wells. Much of the information for the deep saline portions of the Guadalupian Formations are proprietary, but summaries of the permeabilities in these regions have been performed by investigators such as Hiss (1975), Beauheim and Holt (1990), Huff (1997), Hill (2000) and others. Additional published literature is also available from investigations of specific oil fields, and additional core data were also compiled specifically for the San Andres Artesia Fairway. Permeability summaries for the three Guadalupian facies of the Delaware are described below.

Basin Aquifers

Hiss (1975) summarized the permeabilities from approximately 4,500 samples of rock core from the Delaware Mountain Group in Eddy, Lea, Ward, and Winkler Counties. The average permeability of the samples was 6.7 millidarcies (mD). In addition, productivity indexes from two wells at the boundary between Lea County, New Mexico and Loving County, Texas were used to estimate hydraulic conductivity. The estimated hydraulic conductivity was 0.015 feet/day (5.4 mD). Hydraulic conductivities are also available for the upper formation of the Delaware Mountain Group (Bell Canyon) in area of the area of the Waste Isolation Pilot Plant (Beauheim and Holt, 1990). Permeabilities of the Bell Canyon Formation range from 0.02 to 25 feet/day (7.1 to 8,928 mD) depending on the given unit within the Formation. The highest permeabilites are within the sandstone channels of the Bell Canyon, but these channels are not laterally extensive. Most of the units within Bell Canyon and the Delaware Mountain Group fall within the low end of permeability range and act as confining units.

Capitan Reef Complex

The permeability of the Capitan Reef Complex was extensively studied by Hiss (1975). The available data for the reef complex in Eddy and Lea Counties has also been summarized in Huff (1997). The reef complex is continuous in and adjacent to the study area along the northern and eastern margin of the Delaware Basin. The available hydraulic conductivity and permeability data within the deep saline portions of the reef complex is limited to single-well drawdown and recovery tests at a few sparse well locations. Hydraulic conductivities summarized in Hiss (1975) ranged from 1.4 to 25 feet/day (500 to 8,930 mD), and based on this sparse data, Hiss suggested that a hydraulic conductivity of approximately 5 feet/day (1,786 mD) would be reasonable for most areas of the Capitan Aquifer east of the Pecos River. In general, the hydraulic conductivity of the Capitan Reef Complex in this area is approximately two orders of magnitude greater than the hydraulic conductivities of the basin aquifers and the low permeability zones within the shelf aquifers.

Areas of enhanced hydraulic conductivity exist within the Capitan Reef Complex in the Guadalupe Mountains west of the Pecos River and in the Glass Mountains in Brewster and Pecos Counties, extensive systems of caverns, voids, and other enhanced dissolution features exist in the reef complex. These include Carlsbad Caverns and Lechuguilla Cave in the Guadalupe Mountains. The formation of these enhanced dissolution features was likely caused by hydrogen sulfide that was generated from reactions driven by hydrocarbons at the multiple levels of the water table in the geologic past, followed by oxidation to sulfuric acid (Hill, 2000). The transmissivity of the reef complex in the Guadalupe Mountains southwest of Carlsbad is estimated to be 56,000 ft^2/day (Motts, 1968). The development of the enhanced dissolution is a function of the amount of groundwater that has flowed though the complex and the lithology of the formation (limestones tend to dissolve more easily than dolomites). Because the Capitan Reef Complex is more dolomitic in the Glass Mountains (Hill, 2000) and less total flow has likely passed through the reef in this area (Hiss, 1975), the hydraulic conductivity of the reef is likely less in the Glass Mountains than in the Guadalupe Mountains. However, the hydraulic conductivity of the reef in both the Glass Mountains and the Guadalupe

Mountains is likely much greater than the reef in the subsurface of Lea, Ward, Winkler, and much of Eddy and Pecos Counties

Shelf Aquifers

A number of studies have reported on the permeabilities of the San Andres Formation. However, a summary of available permeability data is provided in Hiss (1975). Hiss divided the San Andres Limestone into two areas. The first was the majority of Northwest Shelf and Central Basin Platform east of the Pecos River where average permeabilities are lower. Average permeabilities from cores for the San Andres and the undifferentiated San Andres-Grayburg (where the two are indistinguishable) compiled from a number of sources ranged anywhere from 0.1 to 9.7 mD. Permeabilities for these areas are similar to those of the Delaware Mountain Group and the Artesia Group. The second area included the northern end of the Central Basin Platform (southeastern Lea County) and southern end of the Central Basin Platform (northern Pecos County) where permeabilities in the San Andres are enhanced. Results from two pumping tests were available for the southeastern Lea County area and reported hydraulic conductivities were 0.2 ft/day and 0.3 ft/day (71 to 107 mD). An average permeability of 0.17 ft/day (61 mD) was estimated from analysis of cores in this same region. Data are lacking for the southern end of the Central Basin Platform, but the presence of high capacity wells and good water quality (discussed below) suggests similar permeabilities exist in this region as well. The permeabilities in southeastern Lea County and northern Pecos County are approximately an order of magnitude greater than the rest of the San Andres.

Permeability is also enhanced within flow zones or fairways within the San Andres. The greatest permeabilities in the Artesia Fairway are within the porosity zone of the San Andres (Section 5.2 and 7.2.1.5). The upper San Andres above the porosity zone and the lower San Andres below the porosity zone have permeabilities more similar to those areas outside the Fairway. Permeability within the porosity zone increases progressively from the edges of the Artesia Fairway to the center. Permeabilities at the edges of the Fairway are more similar to the upper and lower San Andres and the portions of the San Andres outside of the Fairway. In the center of the Fairway, permeabilities may be two orders of magnitude or more greater than the edges with as much as 200 feet or more of greater than 30 mD rock. (Trentham, 2011b). For the purposes of this study, the permeability within the Fairway was conceptualized as having zones of equally low permeability throughout the upper and lower San Andres, which are also equal to the permeability of the porosity zone at the edges of the Fairway. The permeability of the porosity zone at the center of the Fairway was assumed to be two orders of magnitude greater than the edges of the Fairway with gradually increasing intermediate permeabilities in between from edge to center. Superimposed on this pattern are the two high permeability zones at northern and southern ends of the Central Basin Platform, which have permeabilities greater than all other portions of the Artesia Fairway. This is demonstrated by pumping centers in the San Andres located in Lea and Pecos county used for water flooding and irrigation respectively.

A number of studies have also reported on the permeabilities of the Artesia Group in and around the oil and gas fields of the Delaware and Midland Basin. The permeabilities of the Artesia group from Eddy, Lea, Ward, and Winkler Counties east of the Pecos River were summarized by Hiss (1975). Permeabilities were summarized from more than 32,000 measurements representing approximately 37,000 feet of core. The average permeability for the Artesia Group was 0.043 feet/day (15.4 mD). An average permeability of 0.073 feet/day (26 mD) was also calculated from 26 typical productivity indexes from 14 different oil wells. Permeabilities may be much higher west of the Pecos River in the Roswell Basin and where the Artesia group is considered part of the reef complex, but over much of the Northwest Shelf and Central Basin Platform, it constitutes a low-permeability confining unit.

7.2.3. Pre-Development Flow Regime

As discussed above, the predevelopment period represents modern time prior to the middle 1920s when large-scale commercial development of oil and gas began. The pre-development period is presumed to be representative of “natural” flow conditions in the basin prior to significant human manipulation. Investigation of the pre-development flow regime is difficult because of the paucity of data available from this time period, and numerous interpretations and generalizations are required. Few regional studies of the hydrodynamic flow within the deep, saline portions of Delaware Basin and the adjacent shelf areas have been performed, and comprehensive studies considering the pre-development flow regime of the entire basin are largely limited to the works of Hiss (1975).

The flow regime through the Guadalupian formations of the Delaware Basin is strongly influenced by the geologic structure of the basin. The basin extends predominantly across the structurally inactive Great Plains, but the western edge of the basin extends into the Rio Grande Rift system. Down-dropping of the Salt Basin Graben has offset and largely disconnected the western edge of the Delaware Basin from the larger Guadalupian flow regime to the east. The main portion of the basin dips east-northeastward at a slope ranging from 105 to 190 feet/mile as measured at the top of the Delaware Mountain Group (Hill, 1996). The eastward tilting of the basin has induced east to northeastward hydrodynamic gradients across the basin (Hiss, 1975). Recharge to the Guadalupian formations in the main portion of the basin occurs predominantly at outcroppings along a belt of uplifted highlands that includes the Sacramento, Guadalupe, Delaware, Apache, Davis, and Glass Mountains.

7.2.3.1. Hydraulic Head

Hiss (1975) compiled hydraulic head data representative of the pre-development condition for the Guadalupian formations in the main portion of the Delaware Basin. A generalized potentiometric surface map adapted from Hiss (1975) is provided as Figure 7.14 (Appendix A-2). Since few reliable head data are available for the predevelopment period, the heads were supplemented to a large extent with head data from the early stage of oil and gas development prior to partial depletion of the reservoirs. Head data were obtained from fluid levels in water wells, initial oil field bottom-hole pressure tests, and from estimated static pressures from drill-stem test (DSTs) and were corrected for salinity when necessary (Hiss, 1975).

Basin Aquifers

The pre-development potentiometric surface maps suggests that heads in the Delaware Mountain Group reaches elevations of more than 3,900 above mean sea level (amsl) feet near recharge areas in the Guadalupe, Delaware, Apache, and Davis Mountains. Heads decline east-northeastward at gradients ranging from 15 to 60 feet/mile. Water flows to the eastern and northern basin margin where it discharged into the laterally adjacent Capitan Reef Complex and the San Andres Formation. Discharge to these formations is evident because of the higher hydraulic head in the Delaware Mountain Group relative to the reef complex and presumably the San Andres Formation at the basin margin. The quantity of discharge is likely very small due to the low permeability of the Delaware Mountain Group. The relatively large head differences between the Delaware Mountain Group and the Capitan Reef Complex (as much as 800 feet) demonstrate the contrast in the permeabilities of the two units.

Capitan Reef Complex

Hydraulic heads in the Capitan Reef Complex are highest in the recharge areas in the Guadalupe and Glass Mountains. Heads in the Guadalupe Mountains are greater than 3,900 feet, and heads in Glass Mountains are as high as 3,300 to possibly 3,400 amsl (Hiss, 1975). Groundwater in the reef complex is unconfined in the Guadalupe and Mountain recharge areas, but occurs under confined conditions from the Pecos River to near the Pecos/Brewster County boundary (Hiss, 1975).

Hydraulic gradients in the Guadalupe Mountains portion of the Capitan Reef Complex are northeastward toward the Pecos River. Hiss (1975) estimated an approximate gradient of 1-2 feet/mile, but other references suggest gradients as high as 4.5 feet/mile (Hill, 1996). Meteoric water recharged in the Guadalupe Mountains traveled generally northeastward along the hydraulic gradient until it primarily discharges to the Pecos River through a series of springs (Carlsbad Spring Complex). Discharge from the springs and water levels in wells in the region respond relatively rapidly to precipitation events, suggesting water recharged in the Guadalupe Mountains discharges within a short period of time: perhaps on the order of few years (Hill, 1996). The rapid discharge is a result of the very high permeabilities in the reef complex west of the Pecos River.

A depression in the potentiometric surface of the Capitan Reef Complex is present around the Pecos River as a result of the groundwater discharge to the river. To the east of the Pecos River and extending to approximately the Eddy-Lea County boundary, the hydraulic gradient is westward with a very gentle slope. A flow divide is present near the Eddy-Lea County boundary that separates the northern limb of the reef complex into an area where water flows westward and eventually discharges into the Pecos River and an area where water flows eastward toward the main body of the complex.

Hydraulic gradients in the Glass Mountains portion of the Capitan Reef Complex are northward. The northward gradient continues through Pecos, Ward, and, Winkler Counties and ranges from approximately 1.5 to 2.4 feet/mile. The lowest heads in Capitan Reef Complex occur in southeastern Lea County. Given that regional gradients are generally eastward, water recharged to the reef complex in the Glass Mountains must eventually discharge into laterally adjacent formations to the east of the reef complex. Hiss (1975) suggested that discharge from the reef complex occurs primarily through enhanced permeability zones in the adjacent shelf aquifers in southeastern Lea and northern Pecos Counties.

Shelf Aquifers

In portions of the Guadalupe Mountains, the Artesia Group (Carlsbad Formation) is highly permeable and considered part of the Capitan Reef Complex. Meteoric water that is recharged to the Artesia Group near the reef front in the Guadalupe Mountains follows hydraulic gradients and drains into the Capitan Limestone, where it eventually discharges into the Pecos River (Motts, 1968). With increasing distance from the reef front (northwestward), the permeability of the Artesia Group typically declines and significant water occurs only in discontinuous perched zones. Water recharged to Artesia group in these areas primarily discharged northeastward to small springs flowing to the Pecos River (Hill, 1996). To the east of the Pecos River, the permeabilities of the Artesia group are low, and flow through the formation is relatively minor. The exception may be in southwestern Lea and northern Pecos

Counties where Hiss (1975) suggested that some water from the Capitan Reef Complex discharges laterally into the formation. Heads and flow patterns in the Artesia group are assumed to be generally similar to those in the underlying San Andres Formation (described below).

Hydraulic heads in the San Andres Formation are primarily greatest in the Guadalupe and Sacramento Mountains where heads may be as high as 4,000 to 5,000 feet amsl (McNeal, 1964). Gradients through San Andres are generally eastward through the Roswell Basin and range from 8 to 25 feet/mile (Hiss, 1975). The majority of water recharged in the Guadalupe and Sacramento Mountains and traveling through the basin discharges to the Pecos River (Barroll and Shomaker, 2003) or to shallow aquifers connected with the river. The San Andres continues east of the Pecos River, but flow is much less than in the Roswell Basin. Because of the discharge to the Pecos River, groundwater circulation and permeability enhancement east of the river has been much less over time. Some flow from the basin may continue to the east of the river where overlying confining units restrict the connection with the Pecos River or possibly from deep circulation beneath the river.

The Artesia Fairway extends eastward from the southern-most portion of the Roswell Basin through northern Eddy and Lea Counties (Figure 7.8, Appendix A-2)). To the east of the Pecos River Hiss (1975) depicted gradients that are southward toward a potentiometric depression north of Carlsbad (Figure 7.14, Appendix A-2). Hiss suggested that water in this region may slowly drain into the reef complex and ultimately back to the Pecos River. However, widespread groundwater extraction from the Roswell Basin began very early (1890s) and pre-development flow patterns immediately east of the Pecos River may be uncertain (DBSA, 1995).

An east-west flow divide with a strong southerly component of flow is present in the Artesia Fairway immediately west of the Eddy-Lea County boundary. The east-west flow divide appears to roughly coincide with the flow divide in the Capitan Reef Complex and separates the flow regime of the Artesia Fairway on the Northwest Shelf into one that flows southwestward and likely ultimately discharges to the Pecos River and one that flows southeastward toward the remainder of the Fairway. Some small amount of vertical or lateral or inflow from adjacent formations to the north is likely occurring in this region to support the east-west groundwater flow divide. Some flow is perhaps from the adjacent, less permeable portions of the San Andres Formation or from deep circulation beneath the Pecos River. Immediately east of the flow divide, gradients through the Fairway are approximately 26 feet/mile until becoming relatively flat in southern Lea County. The change in gradient suggests a change in the permeability of the formation and may be indicative of the enhanced permeability zone in the San Andres on the north end of the Central Basin Platform as described by Hiss (1975). Water discharging from the Capitan Reef Complex over time in this area has likely resulted in enhanced dissolution of the San Andres and increased permeability creating a discharge pathway for reef complex water. The ultimate source of this water would be the Glass Mountain recharge area of the reef complex. Gradients in far eastern Lea County are generally eastward, and flow appears to exit the Artesia Fairway in the vicinity of Hobbs where it presumably continues flowing along other fairways present on the north ends of the Central Basin Platform and the Midland Basin until eventually discharging to streams in central Texas.

The hydraulic gradients through the Artesia Fairway in Ward and Winkler Counties are relatively flat and have an eastward component perpendicular to the length of the Fairway. Though difficult to ascertain, the pre-development potentiometric surface map suggests a slight northward gradient. Assuming northward flow similar to that of the reef complex, flow in the Fairway in Ward and Winkler County would exit the Artesia Fairway along the San Simon Channel in the vicinity of Hobbs.

Hydraulic gradients through the Fairway in Pecos County are eastward. The eastern half of Pecos County is outside the study area of Hiss (1975) and it is difficult to ascertain the gradients in this region. Assuming northward flow in Ward and Winkler County, another flow divide would be present in the Fairway located roughly at the Ward-Pecos County boundary. Hiss (1975) suggested that flow exits the Capitan Reef Complex and is discharged to the shelf aquifers. Discharge from the Capitan Reef Complex into the Artesia Fairway at this area would likely result in a diverging flow pattern similar to that suggested by the potentiometric surface map. The ultimate source of this water would also be the Glass Mountain recharge area for the Capitan Reef Complex.

7.2.3.2 Water Quality

Water quality can be a qualitative indicator of permeability and the quantities of flow through the Guadalupian formations rimming the Delaware Basin since fresh, meteoric water replaces original brines in the formations in amounts proportional to the permeability and the quantity of flow in the formation. Low salinity water quality generally indicates a distant source with potential meteoric contributions and a formation with relatively higher permeabilities and greater quantities of flow passing through the formation. As indicated proximity to the recharge source is also a factor. Regional salinity data for the Guadalupian formations have been compiled by Hiss (1975), McNeal (1964), and LBG-Guyton (2004). These data are supplemented with salinity data compiled specifically for the Artesia Fairway from the USGS (USGS, 2011), the Texas Water Development Board (Texas Water Development Board, 2011), and the Capitan Aquifer Geo database (Texas Water Development Board, 2011b), which are summarized in Appendix A-2. Though water quality data includes samples from the post-development period, the data are believed to be generally representative of the pre-development period as well.

Basin Aquifers

Salinity maps of the Delaware Mountain Group (Hiss, 1974; McNeal, 1964; LBG-Guyton, 2004) indicate that fresh water in the recharge areas of the Delaware, Apache, Davis, and Glass Mountains becomes highly saline within a short distance eastward of outcrop areas and remains consistently very high over the most of the basin (Figure 7.15, Appendix A-2)). Chloride ion concentrations from 50,000 to 200,000 milligrams/Liter (mg/L), and total dissolved solids (TDS) concentration from 150,000 to 300,000 mg/L cover wide areas of the basin (Hiss, 1974; McNeal, 1964). The widespread high salinities in the Delaware Mountain Group are consistent with the low permeabilities and minor amount of flow that occurs through the formation.

Capitan Reef Complex

The salinity of the Capitan Reef Complex is somewhat variable, but is typically less than 25,000 mg/L chloride and is much lower the in the Delaware Mountain Group (Figure 7.16, Appendix A-2). The lowest salinities (<5,000 mg/L chloride) extend eastward from the Guadalupe Mountains and northward from the Glass Mountain and near areas where recharge of meteoric water occurs. The low salinity zone in the Guadalupe Mountains extends eastward to the Pecos River discharge area. To the east of the Pecos River, salinities increase relatively rapidly and attain concentrations in the range of 10,000 to 25,000 mg/L chloride. This higher salinity area extends eastward to the groundwater flow divide near the Eddy-Lea County boundary and suggests that flow through reef complex in this area is less and that little or no recharge from the Guadalupe Mountains reaches this area. This is consistent with the apparent westward gradient (pre-development) to west of the Eddy-Lea County boundary. The higher salinities along the northern limb of the reef complex are likely the result of slow discharge of high salinity water from the adjacent basin and shelf formations (Hiss, 1975).

The low salinity zone in the Glass Mountains extends northward into Pecos, Winkler, Ward, and southeastern Lea County. In western Lea County, salinities increase and are on the order of those in the reef complex between the Pecos River and the Eddy-Lea County boundary. The salinity distribution suggests that the eastern limb of the Capitan Reef Complex is recharged primarily from the Glass Mountains and the majority of flow exits the reef complex before reaching western Lea County. Similar to west of the flow divide between the Pecos River and the Eddy-Lea County boundary, flow through the reef complex in western Lea County to the east of the flow divide is likely relatively stagnant.

Shelf Aquifers

The salinity of the shelf aquifers is highly variable and ranges from having salinities similar to those of the basin aquifers to salinities similar to those of the reef complex. Salinities are low in the Capitan Reef complex from Guadalupe Mountains recharge flowing to the Pecos River where a portion of the water discharges. West of the Pecos River chloride concentration are generally less than 1,000 mg/L indicating the presence of fresh water (Figure 7.15, Appendix A-2). East of the Pecos River, the salinity of the San Andres Artesia Fairway and the overlying Artesia Group formations are much greater and generally range from 50,000 mg/L to 150,000 mg/L chloride (Figure 7.15, Appendix A-2) and 150,000 to 250,000 mg/L TDS (Figure 7.16, Appendix A-2) except at or very near to the reef front. The salinity data suggest that permeabilities are low relative to those west of the Pecos River and that the majority of the meteoric water that is recharged to the shelf aquifers in the Guadalupe Mountains does not reach the east side of the river. It also suggests that despite being laterally adjacent, the shelf aquifers are not well connected to the reef complex in this area. This is consistent with the southwestward gradients exhibited by the shelf aquifers between the Pecos River and the Eddy-Lea County boundary.

In contrast to the northwest shelf, the salinity of the Fairway and the Artesia Group is low in southeastern Lea and northern Pecos County. Chloride concentrations in the San Andres Formation typically range from 5,000 to 10,000 mg/L chloride (Figure 7.15, Appendix A-2)) and 5,000 to 50,000 mg/L TDS (Figure 7.16, Appendix A-2; McNeal, 1964; LBG-Guyton, 2004) in these areas. These low salinity zones coincide with the high permeability zones in the San Andres Formation in isolated areas at the northern and southern end of the Central Basin Platform. The salinities are similar to those of the Capitan Reef Complex, which suggests that lower salinity water from the reef complex is discharging into the San Andres Formation and the Artesia Group in these areas. The salinities in the San Andres Formation are somewhat lower than the Artesia Group in these areas, which suggests a greater proportion of the discharge from the reef complex enters the San Andres.

The salinities in the Artesia Fairway of the San Andres and the overlying Artesia Group in Ward and Winkler Co are high and are similar to those of the northwest shelf east of the Pecos River (Figure 7.15 and 7.16, Appendix A-2). This suggests that the shelf aquifers are not well connected to the reef complex in Ward and Winkler County and those permeabilities are lower than the northern and southern ends of the Central Basin Platform. The low salinities further suggest that most of the discharge from the reef complex occurs in two distinct discharge areas (southwestern Lea and northern Pecos Counties) rather than diffusely across the entire eastern limb of complex.

The low salinity zone in the San Andres Formation in southeastern Lea County extends northeastward to the vicinity of Hobbs and then eastward into Gaines County (Figure 7.16, Figure 7.17, Appendix A-2)). This likely reflects the movement of lower salinity water from the Capitan Reef Complex through the Artesia Fairway and exiting into Gaines County and the Midland Basin. The discharge pathway for lower salinity water entering the Artesia Fairway in northern Pecos County is not evident since high salinity areas surround the low salinity zone and the Artesia Fairway ends in eastern Pecos County.

7.2.3.3. Summary of Pre-Development Flow through the Artesia Fairway.

Pre-development flow patterns through the Artesia Fairway can be surmised from the hydraulic head, gradients, and water quality information for the larger Guadalupian flow system. The data suggest that the majority of the recharge that occurs to the San Andres Formation in its Guadalupe Mountain outcrop area eventually discharges to the Pecos River and does not reach the main body of the Artesia Fairway in Lea, Ward, Winkler, and Pecos Counties. An east-west groundwater flow divide exists at approximately the Eddy-Lea County Boundary with a strong southerly component of flow. The east-west divide hydraulically separates the Fairway in Eddy County and the Guadalupe Mountains from the main body of the Fairway to the east and south. The east-west divide is likely supported by minor amounts of influx/leakage from adjacent formations; possibly from the less permeable areas of the San Andres Formation to the north or deep underflow beneath the Pecos River.

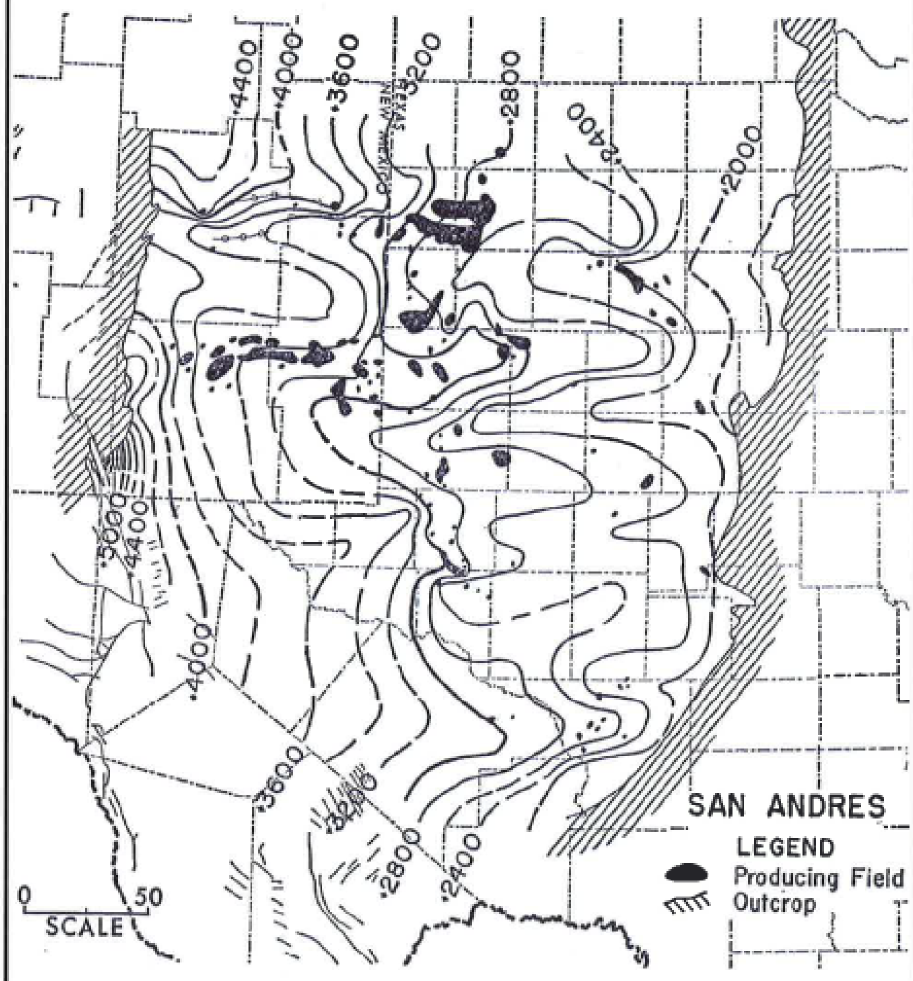
To the east of the divide, water flows eastward at a gradient of approximately 26 feet/mile until the gradient becomes much flatter in southeastern Lea County. In this area, the permeability of the San Andres is enhanced by dissolution and water is likely being discharged to the Fairway from the Capitan Reef Complex. To the south of Lea County, gradients in the Artesia Fairway are relatively flat, and could even be gently northward. Water from the Fairway in western Lea County and in Ward and Winkler Counties likely converges with water from the reef complex in southwestern Lea County were it travels northeastward to near Hobbs and beyond to the Midland Basin.

The Fairway also likely receives water from the reef complex in northern Pecos County, where the permeability of the San Andres is also increased. Flow appears to diverge from northern Pecos County either moving very slowly northward into Ward and/or Winkler County or southeastward into eastern Pecos County. In eastern Pecos County, the southern end of the modeled fairway terminates against an artificial throttling boundary in the southern end of the Fairway.

7.2.4. Post-Development Flow Regime

The post-development flow regime is strongly influenced by groundwater extraction associated with agricultural, industrial, and public water use and for oil and gas exploration and development. In addition to groundwater extraction, flow is further influenced by irrigation returns and by water injected for secondary recovery of oil (water flooding). The extraction and injection of water has changed hydraulic heads and gradients both locally and regionally and has greatly modified and complicated the flow regime within the Guadalupian formations.

The post-development condition is not static and is constantly adjusting to changing flow out of and into the system. Developments within the oil and gas industry have had a particularly large influence on flow patterns over time. Local flow patterns near oil and gas fields or other pumping and injection centers can be especially variable and complex. Given the lack of reliable head, flow, and water use information for the deep, saline portions of the Delaware Basin, there is considerable uncertainty in the understanding of the post-development flow. Therefore, the post-development condition was considered in a more general and regional nature.



Notes:
1. Adapted From McNeal (1964).

RESEARCH PARTNERSHIP TO SECURE ENERGY FOR AMERICA
COMMERCIAL EXPLOITATION AND THE ORIGIN OF RESIDUAL OIL ZONES
DEVELOPING A CASE HISTORY IN THE PERMIAN BASIN
RPSEA Subcontract No. 08123-19

Post-development Potentiometric Surface Map of the San Andres Formation

RPSEA ARCADIS FIGURE 7.18

7.2.4.1 Hydraulic Head

Numerous studies have been performed that quantify the post-development flow regime in the Guadalupian formations. However, most are limited to local sites or in the vicinity of the Guadalupe and Sacramento Mountains where fresh water conditions prevail. Basin-wide studies of the post-development flow regime are limited and tend to focus on the more permeable Capitan Reef Complex. In addition to the sparseness of the spatial distribution of data, there are typically large periods of time between dates that data were collected during which large changes in stresses can occur. Therefore, post-development heads and gradients can only be considered to represent flow patterns within the basin in a general sense.

The regional studies of hydraulic heads and gradients include Hiss (1975) and McNeal (1964). Potentiometric surface maps developed from these studies are provided as Figures 7.17 (Appendix A-2) and 7.18. In addition to these studies, available drill stem tests specific to the San Andres Artesia Fairway were compiled to provide additional information for heads and gradients within the Fairway (Figure 7.19, Appendix A-2)). Fifteen drill stem tests that were performed in a fashion which yielded useful data (out of 738 total tests evaluated) were identified as being within the San Andres Artesia Fairway. These were performed between the dates of 1957 and 1993 and are considered to be representative of post-development conditions. The available head information provides a picture of the large-scale, regional flow patterns within the basin and does not necessarily reflect small-scale features in the flow system such as localized depressions in the potentiometric surface surrounding oil and gas fields.

Basin Aquifers

The post-development regional potentiometric surface in the Delaware Mountain Group is generally similar to the pre-development potentiometric surface (Figure 7.17, Appendix A-2). Gradients are largely similar except for in the vicinity for deep, localized depressions surrounding oil fields. Heads may be depressed several thousands of feet near oil fields (Hiss, 1975), but the depressions likely do not extend a great distance because of the low permeability of the formations. Some lowering of the potentiometric surface likely has also occurred at the margins of the Delaware Basin resulting from lowering of the adjacent, more permeable shelf aquifers and Capitan Reef Complex; however, post-development discharge from the basin aquifers likely has not changed greatly from the pre-development condition.

Capitan Reef Complex

In Eddy County west of the Pecos River, large scale withdrawal of freshwater occurs for municipal and irrigation use. Much of the water from the reef complex that originally discharged to the Carlsbad Spring Complex is now captured by extraction wells. Because of high recharge and the very high permeabilities of the reef complex in this region, potentiometric surface declines have been generally less than 10 feet (Barroll and Shomaker, 2003). Water levels in wells respond relatively rapidly to precipitation events and changes in stage in the Pecos River are indicative of the rapid movement of water.

To the east of the Pecos River, the post-development potentiometric surface of the Capitan Reef Complex has been affected by large-scale withdrawals from water flood supply well fields associated with the secondary recovery of oil centered in Ward and Winkler Counties and from public supply and irrigation wells west of the Pecos River. Pumping from the water flood supply well fields in Ward and Winkler Counties has resulted in head declines of hundreds of feet from the pre-development condition. Head declines are greatest near the Winkler-Lea County boundary where several large water flood supply well fields have been located. Declines in this area were on the order of 1,000 feet in the center of the depression in the mid-1970s (Huff, 1997). Heads have been shown to rise and fall in response pumping from the water flood supply well fields and from oil fields (Hiss, 1975). Recent head information for the region are not available, but long-term declines in the potentiometric surface of the reef complex may have stabilized or reversed as of the late-1970s, presumably as result of decreased pumping (Huff, 1997).

The depressed potentiometric surface in Ward and Winkler County extends over wide areas of the Capitan Reef Complex. To the south, heads are depressed all the way to recharge area in the Glass Mountains. Post-development water levels in the Glass Mountains are 300 to 400 feet lower than during the pre-development condition. To the north, the potentiometric surface is depressed several hundred feet to the Eddy-Lea County Boundary. The widespread depression in heads indicates that groundwater extraction is beyond the recharge available to the reef complex and that large releases of water from storage have occurred.

Near the Eddy-Lea County boundary, the depression in the potentiometric surface becomes greatly reduced. This occurs in the vicinity of the Laguna submarine canyons (Figure 7.12) and a number of other canyons that are incised into northern limb of the reef complex. The reduction of the thickness of the reef complex at the locations of the submarine canyons appears to reduce transmissivities enough to lessen the communication between the main body of the reef complex in Lea, Winkler, Ward, and Pecos Counties and the areas to the west of the Eddy-Lea boundary (though flow is still able to occur through the lower reef complex and possibly through cross cutting fractures in the canyon sediments). Pumping from the water flood supply wells has reduced the magnitude of the groundwater flow divide at the Eddy-Lea County boundary and probably has shifted the divide somewhat to the west.

All post-development flow in the reef complex in Lea, Ward, Winkler, and Pecos counties converges in the vicinity of the northern Ward County near the center of pumping activities (Figure 7.17, Appendix A-2). Therefore, flow in the reef complex in Lea County has been reversed from the pre-development condition. The source of water for the water flood supply well fields is likely primarily from storage release from the unconfined portions of the reef complex in the Glass Mountains and to a lesser extent from storage release from the confined portions of the reef complex and from meteoric recharge in the Glass Mountains (Hiss, 1975).

To the west of the Pecos River, heads in the reef complex have not changed greatly during post-development times. Freshwater municipal and irrigation pumping is widespread, but does not appear to have exceeded the available recharge. Heads fluctuate primarily in response to short-term seasonal trends, weather events, or local pumping conditions. No influence from the water flood well fields in Lea, Ward, or Winkler Counties is apparent. The lack of head decline west of the Pecos River is a result of the high meteoric recharge and rapid movement of water through the highly permeable reef complex in this area. Similar to the pre-development condition, the area west of the Pecos River appears to be hydraulically disconnected from the main body of the reef complex in Lea, Ward, Winkler, and Pecos Counties. Post-development gradients between the Pecos River and the Eddy-Lea County boundary are generally flat (Figure 7.17, Appendix A-2). Gradients may even be slightly reversed (flow to the east), but flow in this region is generally stagnant.

Shelf Aquifers

Similar to the reef complex, heads in the San Andres Fairway and the Artesia Group have been dramatically altered by the extraction and injection of water. To the west of the Pecos River, the groundwater flow regime has primarily been altered by large-scale extraction for irrigation, industrial, and public supply. Though water recharged in the Guadalupe and Sacramento Mountains still flows eastward into the Roswell Basin, the majority of the water that previously discharged to the Pecos River is now withdrawn by pumping wells in the basin (Barroll and Shomaker, 2003). Heads are depressed in areas surrounding pumping centers, especially during the summer irrigation season. Heads in the Artesian Aquifer (San Andres-Grayburg) in the Roswell Basin generally declined from the early 1940s to the late 1960s before stabilizing when regulatory policies began limiting pumping (DBSA, 1995). In the vicinity of the City of Artesia, heads in the carbonate aquifer declined approximately 100 feet

(DBSA, 1995) between 1943 and 1967. During the summer irrigation season, many wells also experience seasonal declines of up to 120 feet (Barroll and Shomaker, 2003). Pumping may have caused some saline water from the east of the Pecos River to move westward into the freshwater portions of the groundwater basin (Barroll and Shomaker, 2003).

To the east of the Pecos River, groundwater flow patterns are highly complex because of extraction and injection associated with oil and gas fields. From the regional potentiometric surface maps, it is not clear whether the east-west groundwater flow divide is present near the Eddy-Lea County boundary (Figures 7.17 and 7.18). However, the high heads exhibited near the divide from DSTs compiled for the San Andres Artesia Fairway would suggest that the east-west divide is still present (Figure 7.19). Flow near the Eddy-Lea County boundary is more strongly in a southern direction (Figure 7.17) than under the pre-development condition suggesting the possibility of slow drainage from the San Andres and Artesia Group into the depressed areas of the Capitan Reef Complex. Regionally, heads along the northwest shelf have probably been lowered 100 to 200 feet from the pre-development condition with much larger declines near oil and gas fields.

In southeastern Lea County where the permeability of the San Andres is higher, the potentiometric surface has been depressed 300 to 400 feet with larger declines locally. Several water flood supply well fields within the San Andres have historically withdrawn water from this area. In addition to the drawdown caused by San Andres supply well fields, drawdown may be caused by pumping from the Capitan Reef Complex, which has also been drawn down several hundreds of feet in this area. Groundwater flow directions in southeastern Lea County have become more toward the southeast in this area, and some groundwater in the San Andres and Artesia Group may actually flow back into the reef complex depending on changes in potentiometric head. Flow out of the Artesia Fairway into Gaines County is likely much smaller under the post-development condition because of the diversion of flow to the water flood supply well fields.

Post-development flow directions in the Fairway in Ward and Winkler County are indeterminate from the regional studies. The regional potentiometric surface maps, drill stem test data, and water chemistry data suggest that gradients are relatively flat, and flow directions may converge toward pumping centers in northern Pecos and southwestern Lea Counties. The potentiometric surface elevations likely have been reduced several hundreds of feet in Ward and Winkler County from the pre-development condition.

Heads in northern Pecos County have likely also been reduced several hundreds of feet as result of water flood supply and irrigation extraction from the San Andres. Extraction from the well fields may have caused water from the Capitan Reef Complex to discharge toward the well fields. Extraction could also be causing gradients for some distance in the Fairway in eastern Pecos County to reverse back toward the well fields, but head data in this region is generally insufficient to define a gradient. Similarly gradients in the Fairway in Winkler County may also be reversed to the south for some distance.

7.2.4.2. Water Use

Large scale withdrawal of freshwater from the Guadalupian formations rimming the Delaware Basin began as early as the 1890s and centered on the Roswell Basin (DBSA, 1995). By 1915, it is estimated that more over 150,000 acre-feet (134 million gallons per day – MGD) of water was being withdrawn from the Artesian Aquifer (San Andres and Grayburg) and has since reached as high as 300,000 acre-feet per year (268 MGD)(Barroll and Shomaker, 2003).

Large-scale freshwater withdrawals from the reef complex to the south began later and now typically range from 15,000 to 20,000 acre-feet per year (13 to 18 MGD)(Barroll and Shomaker, 2003). Withdrawals in both these regions have intercepted much of the meteoric recharge from the Guadalupe and Sacramento Mountains that previously had predominantly discharged to the Pecos River.

Large scale extraction of water from the deep, saline portions of the Delaware Basin and adjacent shelf areas began with the discovery of major oil fields in the mid 1920s. Saline wastewater was produced as a by-product of oil production. The quantity of wastewater produced escalated rapidly before stabilizing in the 1940s. More than 60,000 acre-feet (54 MGD) of saline wastewater was being produced from the basin and adjacent shelf areas by 1970 (Hiss, 1975). The majority of the Guadalupian oil fields of the Delaware Basin are located in the shelf aquifers on the northwest shelf and the western margin of the Central Basin Platform.

Water flooding for the secondary recovery of oil began in earnest in the 1940s as reservoir pressures from the primary production of oil began to become depleted. Water used for water flooding purposes included recycled connate (waste) water, water produced from the Guadalupian Capitan Reef Complex and the San Andres Formation, and water produced from shallower aquifers. Water production increased rapidly from the 1940s and 1950s before stabilizing in the 1960s. Water production from the Capitan Reef Complex alone was estimated to be more than 40,000 acre-feet (36 MGD) in 1969.

Water produced from the reef complex for the secondary recovery of oil has primarily originated from large well fields in southeastern Lea, Ward, and Winkler Counties. Major well fields developed in the reef complex have included the Jal, Dollarhide, El Capitan, Grisham-Hunter, Wink, O'Brien, Wicket well fields and others. A number of well fields also extracted water from the San Andres. These are centered in southeastern Lea County between Hobbs and Eunice and included the Warren-McKee, Janda F, South Penrose, State M well fields and others. These well fields are located within the enhanced permeability zones generally within the Capitan and Grayburg zones, but occasionally San Andres Limestone described by Hiss (1975).

There is little publicly available information for the majority of the San Andres well fields. However, information was compiled for a well field used to supply the Eunice-Monument water-flooding project near Eunice, New Mexico (Figure 7.20, Appendix A-2). The supply wells were developed in the San Andres in the mid-1980s to supply water-flooding operations in the overlying Grayburg Formation (Mitchell and Salvo, 1991; Love et al., 1998). High capacity water wells were constructed through nearly the full thickness of the San Andres with maximum flow rates ranging from 445 to 688 gpm from individual wells (Petroleum Recovery Research Center, 2011). Additional wells were installed to the south in the early 1990s with maximum capacities of 490 and 868 gpm. The combined annual production from the wells reached a maximum of at least 3,200 gpm before gradually declining until the present. Total production from the supply wells over the period from 1995 until the present (the period over which production records are available) was approximately 9,000 million gallons. The large quantity of water produced from these well fields implies the presence of a relatively large source of water nearby to supply the well fields. The presence of the well fields supports the interpretation by Hiss (1975) that the Capitan Reef Complex is hydraulically connected to the San Andres Limestone in southeastern Lea County.

Another area of large scale pumping from the San Andres Limestone exists in northern Pecos Counties (Figure 7.21, Appendix A-2). Water use in this area has historically been used primarily for irrigation, but also for stock watering and for water flooding of oil fields (Armstrong and McMillion, 1961). All wells developed in this region were flowing at the time of completion and the water from some of the wells was simply allowed to discharge out over the ground. The use of water for irrigation purposes is a reflection of the relatively good water quality in the San Andres in northern Pecos County. Though not fresh, the salinity of the water was low enough to use for stock water and to irrigate salt-tolerant crops.

Most of the wells in northern Pecos County were installed in the 1940s and 1950s. Wells were typically constructed through most of the vertical thickness of the San Andres with initial flow rates ranging up to 3,500 gpm (Armstrong and McMillion, 1961). Flow rates in the wells typically declined over time as artesian pressures decreased. Flow records for the northern Pecos County wells during the 1940s and 1950s are lacking, but it has been estimated that 6,200 gpm of San Andres water was produced from the region in 1957 (Armstrong and McMillion, 1961). Of this approximately 3,700 gpm was used for irrigation, approximately 600 gpm was used for water flooding, and approximately 1,900 gpm was allowed to flow over the ground. The presence of these well fields also implies the presence of a large source of water nearby and supports the interpretation by Hiss (1975) that the San Andres carbonate and the proximal Capitan Reef Complex are hydraulically connected locally in northern Pecos County. Current records for the region indicate that the San Andres Limestone is no longer widely used as a source of water (Texas Water Development Board, 2011).

7.2.4.3 Summary of Post-Development Flow through the Artesia Fairway

Post-development flow patterns through the Artesia Fairway are greatly influenced by the extraction and injection of water associated with municipal, industrial, irrigation and oil and gas development activities. The available data suggest that the majority of recharge that occurs to the San Andres in the Guadalupe Mountains that predominantly discharged to the Pecos River is now intercepted by wells. To the east of the Pecos River, flow patterns are highly influenced by extraction and injection associated with oil and gas development, both locally and regionally. Heads have been lowered 100 to 200 feet with greater declines near oil and gas fields. The east-west groundwater flow divide near the Eddy-Lea County boundary may still be present, but the flow direction is primarily south to southeast.

To the east of the Eddy-Lea County boundary, water flows southeastward toward the well fields located in southeastern Lea County between Eunice and Hobbs. Large-scale extraction in this area implies that water from the Capitan Reef Complex also moves to the well fields. Eastward discharge from the Artesia Fairway to the Midland Basin is likely greatly reduced by the diversion of water to the well fields. Regionally, the potentiometric heads in the Fairway in southeastern Lea County have declined 300 to 400 feet (the equivalent to 130 to 170 PSI).

Post-development flow directions in Ward and Winkler Counties are indeterminate from the regional studies, and gradients generally appear to be relatively flat. Regionally, heads likely have been reduced several hundreds of feet in Ward and Winkler and more near oil and gas fields.

Potentiometric heads in northern Pecos County have likely been reduced several hundreds of feet as result of water flood supply and irrigation extraction from the San Andres. The extraction may cause water from the Capitan Reef Complex to move toward the well fields.

Extraction could also be causing gradients for some distance in the Fairway in eastern Pecos County to locally reverse back toward the well fields.

7.2.5 Flow Regime of the Geologic Past

The segment of the geologic past considered by this study is the time period over which the majority of hydrodynamic flow occurred and during which it is believed that hydrocarbons were flushed from the San Andres Artesia Fairway. Hydrodynamic flow in the geologic past is largely controlled by changes in the tectonic setting (including Rio Grande uplift and rifting) and paleo-climate in the regions around and north of the Guadalupe and Glass Mountains. While these changes are generally understood, there is much uncertainty considering the magnitude and timing of events, and conflicting opinions exist among groups of researchers. Attempting to define the flow regime in the geologic past is somewhat speculative, but general configurations can be hypothesized and evaluated based on comparative relationships with the present condition. A summary of the generally understood tectonic and climatic changes in the geologic past that affected hydrodynamic flow is provided in the following sections. The period of the geologic past considered begins in the late Cretaceous when the sea retreated from Region for the final time and the onset of uplift and tilting associated with the period generally described as the “Laramide Orogeny”.

7.2.5.1 Summary of Tectonic Influence on Hydrodynamic Flow

Hydrodynamic flow was likely first induced by uplift and eastward tilting of the region during the Laramide Orogeny in the late Cretaceous-early Cenozoic (80-55 million years ago - MYA). During this time, the region of the Guadalupe Mountains was probably uplifted at least 4,000 feet above sea level (Hill, 2000), and a broadly arched plateau existed across the Delaware Basin. Some researchers suggest that uplift during the Laramide was less than later uplifts (King, 1948) while others believe that most of the elevation of the region was obtained during the Laramide.

The Laramide uplift was followed by a period of relative stability in the Delaware Basin that lasted from the early to middle Eocene (55-43 MYA). Basin and range extensional tectonics likely began to some degree sometime in the late Eocene (30-40 MYA) (Hill, 1996). Uplift that was centered on the present day Rio Grande River began tilting the east flank of the rift (Delaware Basin) to the East. Depositional evidence for rift development along the southern Rio Grande exists from as early as 28 to 31 MYA (Baldridge et al., 1980). The initial period of uplift and eastward tilting is believed to have been slow, broad, and gentle (Chapin and Cather, 1994) with the Delaware Basin not extensively broken by faults (Lindsay, 2001). The Guadalupian formations may have continued unbroken for many miles westward of the current Guadalupian outcrop toward the center of the uplift near the Rio Grande (Lindsay, 2001). Elevations near the center of the uplift may have been greater than 12,000 feet as indicated by Sierra Blanca Peak in the Sacramento Mountains on the Northwest Shelf (DuChene and Martinez, 2001).

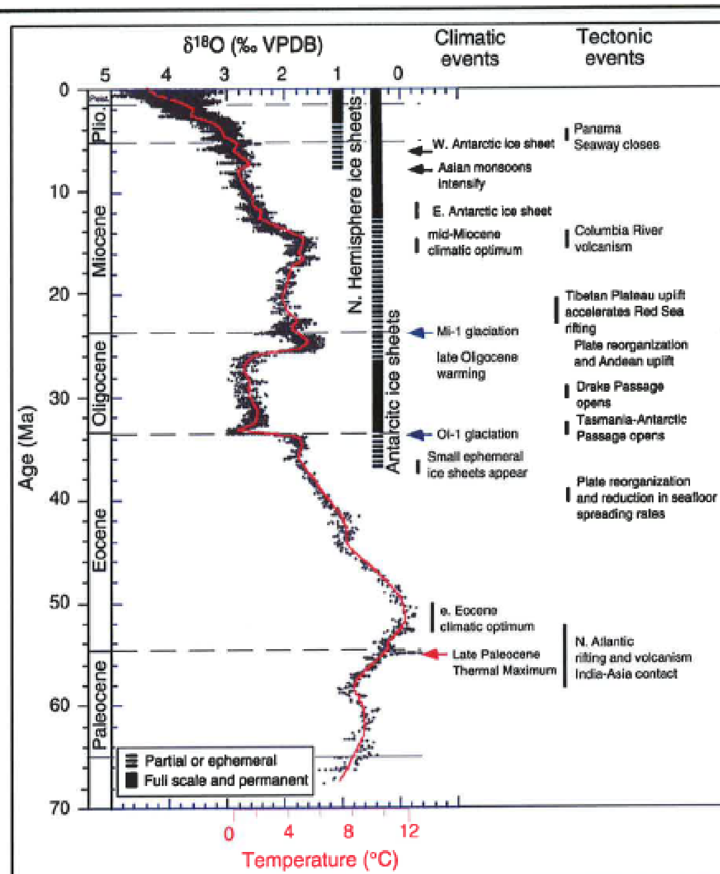
Lindsay (2001) theorized that the broad uplift and tilting of the Region during the initial period of the development of the Rio Grande Rift induced strong hydrodynamic gradients through the Basin. The presence of a connected Guadalupian land mass to the west of the current outcrop area also is theorized to have increased the land area available for meteoric recharge to the Guadalupian Formations relative to the present. The increased recharge and strong hydrodynamic gradients that would have occurred are believed to have flushed many of the hydrocarbon columns in the Delaware Basin to residual saturation.

Beginning in the middle to late Miocene (12-15 MYA), rapid crustal extension began and the area surrounding the Rio Grande was broken into the narrow, steep-sided horsts and grabens that are presently visible (Baldridge et al.,1980). The disconnection of the land areas west of the Guadalupe and Sacramento Mountains would have reduced meteoric recharge and hydrodynamic flow in the Guadalupian formations of the Delaware Basin, eventually leading to current flow conditions (Lindsay, 2001).

Extension along the Rio Grande Rift slowed beginning in the Pliocene (Chapin and Cather, 1994). The final important event in the Delaware Basin was the development of the stream course of the Pecos River. In the late Pliocene, streams flowed eastward across the Delaware Basin from their sources in the mountains (Bachman, 1976). Gradually migration of the Pecos River pirated much of the flow from these streams and extended its length northward until it eventually assumed its present shape. The Pecos River is estimated to have to become hydraulically connected with Capitan Reef Complex at Carlsbad around 600,000 years ago (Hill, 2000). The Pecos River then became a discharge point for flow in the Guadalupian reef complex and the shelf aquifers and further reduced eastward flow through the formations.

7.2.5.2 Summary of Paleo-Climatic Influence on Hydrodynamic Flow

The current climate of the studied region is semi-arid to arid with precipitation ranging from approximately 10 inches in lowland areas to 20 inches at high elevations in the Guadalupe Mountains (TWDB, 2011b; USDA, 2011). However, the climate of the region has changed over the long time intervals of the geologic past and has affected both temperatures and precipitation. Over the past 50 million years, a long-term general cooling trend in global temperatures has occurred (Figure 7.22) with relative peaks in global temperatures in the early Eocene and early Miocene (Hansen and Sato, 2011). Periods of warm global temperatures have been generally correlated to increased precipitation in western United States (US) (Retallack, 2007). The warmer and wetter climates over the Delaware Basin in the geologic past would have resulted in increased meteoric recharge



RESEARCH PARTNERSHIP TO SECURE ENERGY FOR AMERICA
COMMERCIAL EXPLOITATION AND THE ORIGIN OF RESIDUAL OIL ZONES
DEVELOPING A CASE HISTORY IN THE PERMIAN BASIN
RPSEA Subcontract No. 08123-19

Notes:
1. Adapted From Zachos et al., (2001).

Summary of Global Paleo-Tempuratures

RPSEA ARCADIS FIGURE 7.22

to the Guadalupian formations relative to current conditions.

In addition to the general correlation with temperature, precipitation in the geologic past can be inferred from the vegetation patterns present in the region during the past. A distinctive progression from wetter flora to a dryer flora has been recognized in the intermountain southwestern US. From the late Cretaceous to the early Tertiary period, the southwestern US was mostly covered by primitive tropical to sub-tropical forests requiring large quantities of precipitation with no large arid or sub-arid climate zones (West, 1983: Minnich, 2006). A general drying trend at the end of the Eocene led to the disappearance of tropical and subtropical species, and a wide radiation of sub-humid mixed-deciduous and conifer flora occurred (West, 1983: Millar, 1996). These floras still generally required greater quantities of precipitation than currently present, especially during the summer growing months. It has been estimated that at least 14 to 16 inches of summer precipitation (May through August) and 30 to 35 inches of total annual precipitation would be required to support these type of flora (Lyle et al., 2008: Axelrod, 1995).

The mixed-deciduous and conifer flora that are reflective of a wetter climate pattern persisted into the Miocene period, including in the currently arid areas of the southwest (West, 1983). The climate continued to dry after the middle Miocene and by the beginning of the Pliocene (5 MYA), the flora of the southwest shifted to the currently present grassland and scrub-type arid to semi-arid flora (except at high elevations) (Millar, 1996: Lyle et al., 2008). Flow in streams crossing the region became reduced and changed from perennial to intermittent at this time (Bachman, 1976). The climate pattern that began to occur at the beginning of the Pliocoene has remained relatively stable until the present day (Lyle et al, 2008). The cause of the aridification of the southwest has been linked to weakening of summer monsoonal precipitation resulting from cooling of the Pacific Ocean (Lyle et al., 2008) and rain shadows developing on the leeward side of uplifting mountain ranges such as the Sierra Nevada and the coastal ranges (Retallack, 2007).

Although general in nature, the flora present in geologic past can be used to provide a rough estimate of the precipitation that occurred during periods of hydrocarbon flushing in the Delaware Basin. The quantities of precipitation can then generally be correlated to rates of meteoric recharge. Based on the flora present in the southwestern US, it is hypothesized that at least 14 to 16 inches of summer precipitation and 30 to 35 inches of total precipitation occurred in the Region during the late Oligocene and early Miocene when flushing of hydrocarbons is theorized to have occurred.

7.2.5.3 Pecos County Sulfur Mines

Greater recharge and hydrodynamic flow through the Guadalupian system in the geologic past would require a greater discharge pathway or higher piezometric gradients for the water than that which currently exists. A discharge pathway is theorized to have existed at the southern end of the Central Basin Platform at the locations of a linear chain of sulfur deposits in northern Pecos County (Fort Stockton Sulfur District). Native sulfur in Fort Stockton Sulfur District is associated with bioepigenetic carbonates, which indicates that hydrocarbons were involved in the formation of the sulfur.

The native sulfur in the Fort Stockton Sulfur District is believed to have formed as a result of the microbial metabolism of hydrocarbons in sulfate-bearing groundwater (Hill, 1996). Microbial sulfate reduction produces hydrogen sulfide and bioepigenetic carbonates according to the following reaction:

$$Ca^{2+} + 2SO_4^{2-} + 2CH_{4(hydrocarbons)} + 2H^+ = 2H_2S + CaCO_{3(limestone)} + 3H_2O + CO_2$$

Hydrogen sulfide then becomes oxidized to form native sulfur by one of several reactions such as following:

$$2H_2S + O_2 + 2H^+ = 2S_{(native\ sulfur)}$$

The source of the hydrocarbons is thought to be from the flushing of hydrocarbons from the Guadalupian and Leonardian (San Andres Artesia) Fairway; predominantly in the geologic past when hydrodynamic flow was greater. A combination of a structural anticline that exists within and above the San Andres in northern Pecos County (Hentz et al., 1989) (Figure 7.9) and the west-northwest lineament responsible for the southern limit of the Central Basin Platform provided a trapping mechanism for migrating hydrocarbons within and The sulfur deposits are found in the Seven Rivers, Yates, and Tansill Formations of the Artesia Group and in the overlying Salado Formation, but mostly within the Tansill and Salado Formations. Hydrocarbon-bearing groundwater likely moved upward along fractures and collected above the structural highs and came into contact with overlying evaporites to form chimneys of native sulfur and bioepigenetic carbonates (McNeal and Hemenway, 1972).

The chimneys of native sulfur in northern Pecos County are evidence of discharge pathways for hydrodynamic flow that are now blocked. The chimney features may have been the major regional discharge pathway for much of the Artesia Fairway. Water passing through the lineaments likely would have discharged to the overlying Rustler Aquifer and either to surface or at some distance to the east. The ability of the lineaments to transmit water may have been the restriction point for flow through the Fairway.

7.2.5.4. Hypothesized Flow Regime

Flow in the late Oligocene and early Micoence was likely greater than it is today due to changing climatic and tectonic conditions. One tectonic change that has likely influenced flow is the hypothesized unbroken extension of the Guadalupian formations to west of their current recharge areas in the Guadalupe and Sacramento Mountains. The Guadalupian formations would have extended to much higher elevations in the late Oligocene and early Miocene, which would have provided a much larger landmass for meteoric recharge to occur (Figure 7.23, Appendix A-2). The effect on the San Andres Artesia Fairway on the Northwest Shelf would have been increased heads and hydraulic gradients and consequently, increased hydrodynamic flow eastward. The influence of the tectonic changes on the Capitan Reef Complex was likely not as great since the position of the reef complex never extended much further west than the Guadalupe Mountains (Figure 7.3). Flow through western limb of the reef complex was likely south and southeastward into Hudspeth and Culberson Counties and did not contribute flow to the northern limb of the complex.

Another factor affecting flow would be the absence of the Pecos River in the area prior to approximately 600,000 years ago. The Pecos River currently provides a discharge pathway for the recharge areas of the San Andres Formation and Capitan Reef Complex in the Guadalupe and Sacramento Mountains to the west. With the absence of the Pecos River, the groundwater flow divide present in the Capitan Reef Complex and the east-west divide in the Fairway at the Eddy-Lea County boundary would not have existed. Meteoric recharge would have continued to travel eastward into Lea County in both San Andres Artesia Fairway and the Capitan Reef Complex. In the reef complex, however, flow would still have been somewhat limited by the Laguna submarine canyons near the Eddy-Lea County Boundary. The quantity of flow would have been controlled by the transmissivities of the thinner sections of the reef complex beneath the submarine canyons. Cross cutting fracture systems through the canyon sediments may have also influenced flow (Hunt et al., 2002).

The additional effect of the increased hydrodynamic flow in the northern limb of the reef complex would have been the greater discharge from the reef complex to the San Andres Formation. Flow through the northern limb of the reef complex may have been sufficient to supplant the Glass Mountain recharge area as the primary source of discharge to the San Andres in southeastern Lea County.

At the southern end of the Central Basin Platform, the hypothesized regional discharge points at the locations of the sulfur mines in northern Pecos County would have reduced heads in this area. This would have promoted southward flow through the Artesia Fairway on the west side of the Central Basin Platform and may also have allowed for increased discharge from the Capitan Reef Complex into the San Andres. Enhanced dissolution from this discharge pathway would explain the formation of the high permeability zone in the San Andres in northern Pecos County and the ability of the San Andres to support high capacity irrigation withdrawals in this region. Discharge from the reef complex in this area is also likely to have reduced (or halted) the northward flow of water within the reef complex into Ward and Winkler Counties.

7.2.6 Water Budgets

Flows for the Artesia Fairway for the pre-development condition, post-development condition, and for the geologic past were estimated from the hydraulic properties, hydraulic gradients, and physical dimensions of the formation. Flows through the formations were calculated using the Darcy equation for groundwater flow as shown in the following equation:

$$Q = 0.005195KiA$$

Where: Q = the volumetric rate of flow (gpm)
K = the hydraulic conductivity of the formation (feet/day)
i = the hydraulic gradient (feet/feet)
A = the cross sectional area of formation through which flow occurs ($feet^2$)

The water budget analysis focused on the portions of the Artesia Fairway that affect flow in Ward and Winkler Counties and serve as the basis for constructing the groundwater flow model. The water budget analysis also considers flow in other Guadalupian formations where they contribute flow to the Fairway.

7.2.6.1 Pre-Development Water Budget

The pre-development water budget for the Artesia Fairway was estimated from the pre-development potentiometric surface map of Hiss (1975) (Figure 7.14). The recharge area for the Artesia Fairway is in the Guadalupe Mountains. The total recharge to the “Artesian Aquifer” (San Andres and Grayburg) of the Roswell Basin is related to annual precipitation in the region and typically ranges from 170,000 to 380,000 acre-feet per year (152 to 339 MGD)(DBSA, 1995). However, the majority of this recharge eventually discharges to the Pecos River. The portion of the Artesia Fairway west of the east-west groundwater flow divide at the Eddy-Lea County boundary is generally disconnected from the rest of the Fairway to the east.

The east-west groundwater flow divide at the Eddy-Lea County boundary must be supported by some inflow from adjacent formations. Since hydraulic gradients toward the Fairway are from the north in this area, it is likely that the majority of the inflow is also from the north; likely from the less permeable portions of the San Andres Formation. Flow into the Fairway in this area was estimated to be 1.2 gpm based on the length of the Fairway east of the groundwater flow divide where gradients have a southerly component (135,000 feet), the average thickness of the northern edge of the Fairway over this distance (1,522 feet), the average hydraulic gradient (21 feet/mile), and the estimated hydraulic conductivity along the northern edge of the Fairway (0.1 mD or 0.00028 ft/day). Since the permeabilities of the formations to the north of the Fairway are relatively small, the inflow into the Fairway in this area is also relatively small.

In southeastern Lea County, water from the Capitan Reef Complex discharges into the Artesia Fairway. The ultimate source area for this water is the Glass Mountains. Approximately 20 to 23 inches of annual recharge occurs to the highly permeable portions of the reef complex in Guadalupe Mountains (Hill, 1996), but this water discharges to the Pecos River and does not reach southwestern Lea County. Recharge rates specific to the Capitan Reef Complex in the Glass Mountains have not been studied (Middle Pecos Groundwater Conservation District, 2010); however, the quantity of water moving northward through the reef complex immediately to the north of the Glass Mountains can be estimated from the pre-development hydraulic gradients in this area. The northward gradient though Pecos County is approximately 53 feet/mile (Figure 7.14). The average width of the reef complex is approximately 48,000 feet and the average thickness is approximately 1,000 feet (Standen et al., 2009). The conceptualized hydraulic conductivity of 1,000 mD (2.8 feet/day) was assumed for the reef complex in this area. Though somewhat less than the hydraulic conductivity proposed by Hiss (1975), the lesser value accounts for flow restrictions caused by submarine canyons along the eastern limb of the reef complex and for some flow loss to the overlying Rustler Aquifer in Pecos County (Melzer, 2011). The flow moving northward from the Glass Mountains is estimated to be 330 gpm under the pre-development condition.

Though some discharge from the reef complex may occur to the San Andres Formation and the Artesia Group in northern Pecos County, the discharge is likely small because there are no significant discharge points for flow in these formations at the southern end of the Central Basin Platform. Water flowing northward from the Glass Mountains would for the most part, continue to travel northward into Ward, Winkler, and southeastern Lea County.

Water moving northward through the reef complex discharges to the San Andres Limestone and the Artesia Group in southeastern Lea County. Based on the relative permeabilities and thicknesses in contact with the reef complex (estimated from cross sections), it is estimated that approximately 85 percent of the flow would discharge into the San Andres Limestone and approximately 15 percent would discharge into the Artesia Group. Therefore, approximately 280 gpm of the total 330 gpm would discharge into the San Andres Limestone and approximately 50 gpm would discharge into the Artesia Group. Water discharging into the Artesia Fairway from the reef complex would combine with flow moving eastward along the Fairway from western Lea County and would exit into Gaines County and the Midland Basin along the area of the San Simon Channel (281 gpm total).

Flow moving northward through the Fairway in Ward and Winkler Counties would also converge in southwestern Lea County and then exit into Gaines County. This quantity of flow would be relatively small (perhaps a few gpm) relative to quantity of water discharging from the reef complex in southeastern Lea County because hydraulic gradients through the Fairway in Ward and Winkler County are relatively flat. Water would also move southeastward along the Fairway from northern Pecos County to the end of Fairway in eastern Pecos County. The quantity of water moving in this direction would also be small (a few gpm or less) because of the small amount of discharge from the reef complex in Pecos County and the lack of a significant discharge point for the water further to the east. The water budget components for the pre-development condition are summarized in Table 7.1.

Table 7.1. Summary of Estimated Pre-Development Water Budget

Boundary	Flow Direction	Quantity (gpm)
Eddy-Lea County Boundary	Inflow	1.2 gpm
Capitan Reef Complex - Southeastern Lea	Inflow	280 gpm
Lea-Gaines County Boundary	Outflow	281 gpm
Capitan Reef Complex – Northern Pecos	Inflow	<1 gpm
Eastern Pecos County	Outflow	<1 gpm

7.2.6.2 Post-Development Water Budget

The post-development water budget for the Artesia Fairway was estimated from the post-development potentiometric surface map of Hiss (1975) (Figure 7.17). Because injection and withdrawal from the system was variable over time, gradients and flow are also variable and, therefore, the post-development water budget is general in nature.

As with the pre-development condition, the portion of the Artesia Fairway west of the Eddy-Lea County Boundary is isolated from the remainder of the Fairway by an east-west groundwater flow divide, where flow is predominantly southerly. Inflow to Fairway still occurs from adjacent formations to north. Hydraulic gradients toward the Fairway from the north are somewhat steeper than the pre-development condition as a result of pumping (35 feet/mile), and the estimated inflow is slightly larger at 2 gpm. In southeastern Lea County at the discharge point for the Capitan Reef Complex, flows are quite different. The large-scale withdrawals from the reef complex have created a depression in the potentiometric surface centered on Ward County, and gradients in the reef complex are reversed for some distance to the north. Discharge into the Fairway from the reef complex is greatly reduced and may have halted or even become reversed at times depending on the relative amounts of pumping from the well fields in the reef complex and in the San Andres between Eunice and Hobbs. Gradients in the reef complex are generally parallel (to the southeast) to those in the Fairway, which suggests that if discharge from the reef complex is occurring, it is likely a few tens of gallons per minute or less.

Similar to the pre-development condition, flow moving northward through the reef complex in Pecos County resulting from recharge in the Glass Mountains is approximately 330 gpm for the post-development condition. The quantities of water extracted from the reef complex (approximately 19,000 gpm annually in the late 1960s) are far greater than the available natural recharge. This indicates under the post-development condition, water recharged in the

Glass Mountains does not reach southeastern Lea County, and the source of most of the extracted water is from storage.

Since discharge from the reef complex is much less, flow eastward from the Fairway and into Gaines County and the Midland Basin would also be greatly reduced. Total flow would be the sum of the flow moving eastward along the Fairway from western Lea County, the inflow reef complex, and the small amount of flow moving northward through Fairway from Ward and Winkler County. The total is estimated to be somewhere between a few gpm and 20 gpm.

No heads are provided on the post-development potentiometric surface map for the Artesia Fairway at the southern end of Central Basin Platform (Figure 7.17). However, heads independently estimated from the DST data compiled for the Fairway range from 2,531 to 2,849 feet. These are for the most part lower than the heads depicted on the post-development potentiometric surface map for the adjacent Capitan Reef Complex, which would suggest that water is discharging from the reef complex. The quantity of water discharging from the reef complex has likely been variable during post-development times because of the variable pumping from the well fields in the San Andres in northern Pecos County. In the 1940s and 1950s when extraction from the well fields was large (approximately 6,200 gpm in 1957), discharge from the reef complex may have been hundreds of gallons per minute or more with much of this water coming from storage. In more recent years when extraction from the well fields has been small, discharge from the reef was also likely small. Head data in this region of the Fairway are too sparse to provide a reliable estimate of flow from the reef complex to the Fairway.

Some of the discharge from the reef complex likely would likely have bypassed the San Andres well fields and moved north along the Fairway through Ward and Winkler County and also southeastward through the Fairway into eastern Pecos County. Similar to the pre-development condition, flow southeastward through the Fairway would be small because of the lack of a significant discharge point for the water further to the east. The estimated post-development water budget for the post-development condition is summarized in Table 7.2.

Table 7.2. Summary of Estimated Post-Development Water Budget

Boundary	Flow Direction	Quantity (gpm)
Eddy-Lea County Boundary	Inflow	2 gpm
Capitan Reef Complex - Southeastern Lea	Inflow	0 - 20 gpm
Lea-Gaines County Boundary	Outflow	2 - 22 gpm
Capitan Reef Complex – Northern Pecos	Inflow	Variable
Eastern Pecos County	Outflow	<1 gpm

7.2.6.3 Water Budget for the Geologic Past

A conceptualized water budget was also developed for the geologic past. The largest difference between the pre-development flow regime and the flow regime of the geologic past was the absence of the Pecos River and the unbroken extension of the San Andres Formation to the west of the Guadalupe and Sacramento Mountains. The increased land area and the wetter climate in the geologic past would have resulted in increased meteoric recharge to the Fairway, increased hydraulic gradients, and increased flow across the Northwest Shelf. The east-west flow divide near the Eddy-Lea County boundary would have been absent.

The elevation of the San Andres Fairway to west of the Guadalupe Mountains prior to fault blocking in the middle to late Miocene was estimated based on current high-point elevations of the San Andres Formation in the Sacramento Mountain horst. Though the San Andres Formation may have extended to higher elevations to the west across the Tularosa Basin, San Andres Mountains, and perhaps beyond, the points in the Sacramento Mountains provide a more certain expression of the elevations of the formation in the geologic past.

Two stratigraphic high points of the San Andres Formation within the Sacramento Mountains were located which are thought to be representative of the elevations of the unbroken San Andres land mass in the late Oligocene and early Miocene. These include Pajarito Mountain in Northeastern Otero County and Sacramento Canyon in central Otero County, New Mexico (Figure 7.24, Appendix A-2). At Pajarito Mountain, the high-point elevations of the San Andres are approximately 8,610 feet-amsl for the top of the formation and 8,220 feet-amsl for the bottom of the formation (Kelley, 1971). At Sacramento Canyon, the high-point elevations are approximately 9,340 ft-amsl for the top of the formation and 8,240 feet-amsl for the bottom of formation (Livingston Associates and John Shomaker and Associates, 2002).

The hydraulic gradient along the Northwest Shelf was estimated from the San Andres high point elevations in the Sacramento Mountains. It is presumed that in the late Oligocene and early Miocene, groundwater elevations in the San Andres would have been somewhere between the top of formation and bottom of formation elevations represented by the high point elevations at Pajarito Mountain and Sacramento Canyon. For the purposes of this study, it was assumed that the mid-point elevation between the top of formation and bottom of formation is representative of the groundwater elevation in the geologic past. The mid-point elevations are 8,415 feet-amsl at Pajarito Mountain and 8,790 feet-amsl at Sacramento Canyon.

The head at the Eddy-Lea County boundary (location of the model boundary) in the geologic past was estimated assuming a linear hydraulic gradient between the estimated groundwater elevations at Pajarito Mountain and Sacramento Canyon and the groundwater elevations (pre-development) at the western edge of the high hydraulic conductivity zone in the Fairway in southeastern Lea County (3,000 ft-amsl). The gradient estimated from Pajarito Mountain was 45.1 feet/mile (assuming the elevation could be projected southward to the east-west trend of the Fairway along the Northwest Shelf), and the gradient estimated from Sacramento Canyon was 43.7 feet/mile. Based on these gradients, the estimated heads at the Eddy-Lea County boundary are 4,059 feet-amsl and 4,026 feet-amsl, respectively (average of 4,043 feet-amsl). This is several hundreds of feet higher than the heads representative of the pre-development condition (3,300 to 3,570 ft-amsl).

Based on the estimated hydraulic gradient, the estimated hydraulic conductivities of the three conceptualized layers of the San Andres Limestone within the Fairway on the Northwest Shelf (0.1 to 10 mD or 0.00028 to 0.028 ft/day), the width of the Fairway (133,000 feet) and the thickness of each layer of the San Andres (314 feet upper San Andres, 642 feet porosity zone, and 529 feet lower San Andres). The flow across the northwest shelf at the Eddy-Lea County boundary was estimated to be 49.7 gpm.

The absence of the Pecos River in the Late Oligocene and early Miocene would also have allowed recharge to the Capitan Reef Complex in the Guadalupe Mountains to travel eastward across the Northwest Shelf. However, the flow across the Northwest Shelf would still have been restricted by the Laguna submarine canyons and other canyons on the Northwest Shelf (Figure 7.13). The flow restriction present at the Eddy-Lea County boundary associated with the Laguna submarine canyons provides a good location to estimate flow across the Northwest Shelf since the restriction point probably controlled the amount of flow through the reef complex in this region. Hiss (1975) estimated the transmissivity of the reef complex near the sub-marine canyon to be 5,000 square feet per day (ft^2/day).

Gradients across the Northwest Shelf in the reef complex in the geologic past are not known. Because the position of the reef complex did not extend much further westward in the geologic past than it does today, heads would likely not have been as elevated as in the San Andres. However, heads would still have been greater than the present due to the lack of a discharge point at the Pecos River and the wetter paleo-climate. To estimate a flow through the reef complex, a gradient equal to the pre-development gradient through the San Andres Artesia Fairway was assumed (2.3 feet/mile). Utilizing this gradient and the approximate total width of the reef complex at the Eddy-Lea County boundary (50,000 feet) and the transmissivity from Hiss (1975), it was estimated that approximately 560 gpm of water flowed through the reef complex across the Northwest Shelf in the geologic past.

Water flowing through the reef complex would have traveled eastward into southeastern Lea County. At least a portion of this water would have discharged into the San Andres Artesia Fairway and the Artesia Group. Because the increased flow across the Northwest Shelf would have resulted in increased heads in this region, it is possible that a portion of the flow also moved southward into Ward and Winkler County, depending on the relative heads further south. Water discharging into the San Andres Artesia Fairway would have combined with water traveling eastward through the Fairway along the Northwest Shelf and would have either exited the Fairway into Gaines County and the Midland Basin or depending on heads, traveled southward through Ward and Winkler County.

Another difference between the pre-development flow regime and the flow regime of the geologic past is the quantity of meteoric recharge to the Capitan Reef Complex in the Glass Mountains. Though the recharge area for the reef complex in the Glass Mountains was likely not substantially larger than it is today, the wetter climate during the geologic past would likely have increased recharge rates. As described in Section 7.2.5.2, it is likely that at least 14 to 16 inches of summer precipitation (May through August) and 30 to 35 inches of total precipitation would have been necessary to support the flora present in the region in the late Oligocene and early Miocene. This is approximately double the current precipitation rates of 7 to 8 inches in the summer and 16 to 18 inches annually (Middle Pecos Groundwater Conservation District, 2010). Though precipitation in the late Oligocene and early Miocene may have been greater than the minimum 30 to 35 inches, the karstic porosity currently present in the Glass Mountains likely would have been less well developed in geologic past (Hill, 2000). This would have tended to counteract the effect of increased precipitation. Therefore, the minimum increase in precipitation was assumed for the purposes of this study. Assuming a doubling of the precipitation occurred in the Glass Mountains, the flow moving northward through the reef complex would also have doubled (660 gpm).

Water moving northward from the Glass Mountains would either discharge into the San Andres Limestone and Artesia Group at Pecos County or continue moving northward through the reef complex depending on the heads present to north. The majority of any water discharging to

San Andres would likely travel to the regional discharge points at locations of the sulfur deposits in northern Pecos County.

The flow through much of the Artesia Fairway during the geologic past is not well understood and is focus of this modeling study. The estimated flow inputs to Fairway in the geologic past are summarized in Table 7.3. The remaining components of the water budget were studied through the development of a groundwater flow model as described in the following section.

Table 7.3. Summary of Estimated Water Budget Inputs to Artesia Fairway in the Geologic Past

Boundary	Flow Direction	Quantity (gpm)
Eddy-Lea County Boundary	Inflow	49.7 gpm
Capitan Reef Complex - Flow Across Northwest	Inflow	560 gpm
Capitan Reef Complex – Glass Mountain	Inflow	660 gpm

7.3. Groundwater Flow Model Development

A groundwater flow model was developed to provide an analytical tool to further investigate the flow system through San Andres Artesia Fairway during the geologic past and evaluate the mechanisms by which flushing of hydrocarbons may have occurred. The flow modeling investigation is conceptual in nature due to the lack of observational data from past geologic events, but provides insight into the processes and inputs controlling hydrodynamic flow and quantifies the effect of variation in uncertain parameters. The representativeness of the model was verified by performing calibration simulations of the conditions during the pre-development and post-development times during which observational data were available and adjusting the model as necessary to conform to those data.

The groundwater flow model is a mathematical representation of the conceptual site model described in the previous sections and uses the method of finite-differences to calculate flow through a multi-layered system of rectangular blocks that represent the hydrogeologic system. Flow through each of the blocks is computed based on mass balance constraints and Darcy's Law under a set of input conditions defined during development of the conceptual site model.

The model was constructed using the public-domain modeling code MODFLOW 2000 developed by the United States Geological Survey (Harbaugh et al., 2000). The input files required by MODFLOW 2000 were generated using the graphical pre-processing and post-processing software Groundwater Vistas developed by Environmental Simulations, Inc (ESI, 2007). Much of the information used to develop the site conceptual model (heads, boundaries, formation elevations, etc.) were stored electronically as shape files using the ARCGIS (ESRI, 2009) geographical information system software and Surfer (Golden Software, Inc., 2002) and were imported into the modeling environment as necessary.

7.3.1. Model Descritization

The groundwater flow model was developed using a uniform grid with constant cell spacing of one-half mile by one-half mile (Figure 7.25, Appendix A-2). The grid consists of a total of 374 rows and 160 columns oriented with the long axis of the San Andres Artesia Fairway along the west side of the Central Basin Platform (21 degrees west of north). The active portion of the model grid includes the areas of the San Andres Formation associated with the Artesia permeability trend along the Northwest Shelf and Central Basin Platform and extends from near the Eddy-Lea County boundary to the end of the permeability trend in eastern Pecos County at the southern end of the Central Basin Platform.

Vertically, the model was divided into three layers that corresponded to the conceptual site model and consisted of the upper San Andres (layer one), the porosity zone (layer two), and the lower San Andres (layer three). The contacts between boundaries were defined based on interpretations of logs from oil and gas exploration. Top elevations for the geologic formations of the Delaware Basin were obtained from the Information Handling Services (IHS) PETRA (energy information, software, & solutions software) (IHS PETRA, 2011). Formations in the database included the Rustler, Tansill, Yates, Seven Rivers, Queen, Grayburg, San Andres, Glorieta, Blinebry, Paddock, Leonard, Bone Spring, Clear Fork, Yeso, Tubb, Drinkard, Abo, Abo Reef, Wichita - Albany, Wolfcamp, Strawn, Silurian, Fusselman, Montoya, McKee, Waddell, and Ellenburger. Elevations for the top of the San Andres and the top of the Glorieta (bottom of the San Andres) were used as a starting basis to define the upper and lower vertical boundaries of the model.

The vertical model boundaries were later refined using data gathered from USGS (USGS, 2011), the Midland Energy Library (2011), Railroad Commission of Texas (2011), NM WAIDS (2011), and GO-TECH Petroleum Web (Petroleum Recovery Research Center, 2011) compiled for five counties: Pecos, Ward and Winkler Counties in Texas and Eddy and Lea Counties in New Mexico. The data consisted of well completion information, water chemistry data (including total dissolved solids), and drill stem test (DST) information including pressure data and charts. The data acquired from the five counties were reduced to data from the wells located within the boundaries of the Fairway. The data were further reduced to entries between 3,000 and 7,000 feet below ground surface. The San Andres Formation is found between these depths over most of the five-county area. Flowing fluid electric conductivity logs from the remaining wells were evaluated to determine the elevations of the geologic formations: Rustler, Tansill, Capitan, Bell Canyon, Yates, Seven Rivers, Queen, Cherry Canyon, Middle Queen, Goat Seep, San Andres, San Andres Pie Marker, Brushy Canyon, McKnight Shale, Glorieta, Cutoff, Clear Fork, Bone Spring, Tubbs and Wichita-Albany. Using the fluid electric conductivity log signatures, the data were used to define the porosity zone within the Fairway, isolating the San Andres Formation and the top and bottom of the higher permeable zone within the San Andres.

Contact elevations were compiled (Appendix B), plotted, and interpolated using kriging within the Surfer environment (Golden Software, Inc., 2002). The kriged surfaces were then imported into the modeling environment and an interpolated contact elevation was applied to each grid cell for each layer. An isopach (thickness) map for the porosity zone was shown on Figure 7.10 (Appendix A-2). Isopach maps for the upper and lower San Andres are shown on Figures 7.26 and 7.27 (Appendix A-2).

7.3.2. Model Boundaries

The vertical boundaries of the model domain were defined as the top and bottom of the San Andres Formation. Flow through the Artesia Fairway is predominantly horizontal and it was assumed that vertical flow upward into overlying units and downward into underlying units is insignificant. The lateral boundaries of the model were defined as the edges of the San

Andres Artesia permeability trend (Figure 7.28, Appendix A-2). Horizontal dimensions are discussed in section 5.2.1, and vertical units are discussed in section 5.2.1. Lateral inflow from the adjacent Delaware Mountain group is small and has little effect on flows within the Fairway. The majority of the area to the west and south of the Fairway and encompassed by the Delaware Mountain Group was represented with no-flow cells. Lateral flow to and from the less permeable portions of the San Andres Limestone to the north and east of the Artesia Fairway trend were also represented with no-flow cells because of the small amount of flow through these areas.

A linear boundary was also defined within the San Andres along the Northwest Shelf near the Eddy-Lea County border where an east-west groundwater flow divide was depicted within the shelf aquifers by Hiss (1975)(Figure 7.28, Appendix A-2). Specified head boundary cells were assigned to all three of the model to reproduce heads at the east-west flow divide. The gradients near the east-west divide have a strong southerly component. Flow introduced into the model by the specified head cells represents the inflow to Fairway from adjacent formations from the north.

Discharge from the Artesia Fairway into Gaines County and the Midland Basin was simulated with head-dependent flux boundary cells (general head boundary)(Figure 7.28, Appendix A-2). The head-dependant flux cells allow flow across the boundary in proportion to the difference between simulated head at the boundary and the head assigned to boundary cell, which represents the head in the area beyond the model domain. The flow across the boundary is also proportional to conductance of the boundary cell, which is a function of the hydraulic conductivity assigned to the cell and the dimensions of the formation the cell represents. Flow across a given boundary cell is represented by the following equation:

$$Q = C * (head_{boundary} - head_{active\ cell})$$

Where: Q = flow

$head_{boundary}$ = head assigned to the boundary condition

$head_{simulated}$ = simulated head in the active model cell

C = conductance = kbw/d

k = hydraulic conductivity assigned to the cell

b = saturated thickness of formation represented by the cell

w = width of formation represented by the cell

d = distance to the boundary

The head-dependant flux boundary also allows flow into the model domain if gradients are reversed. The conductance was defined for each head dependant flux boundary cell according to the conceptualized hydraulic conductivity of the Fairway at the given cell and the dimensions of the Fairway represented by the cell. The head-dependant flux cells were assigned to all three model layers.

Flow exiting the Fairway from the southern end of the Central Basin Platform in eastern Pecos County was also simulated with head dependant flux cells. Because the higher permeability trend of the Artesia Fairway ends beyond eastern Pecos County, the conductance term was assigned to the boundary was based on a lower permeability that is more representative the of San Andres Formation beyond the end of the Fairway. The model boundary allows flow to exit the Fairway in this area, but the quantity of flow is limited according to the hydraulic properties San Andres further down gradient.

Two additional boundaries were included to represent discharge from the Capitan Reef Complex in accordance with the conceptualization of Hiss (1975). Head-dependant flux boundaries were assigned to the western lateral flank of the Fairway in southeastern Lea County and in northern Pecos County (Figure 7.28, Appendix A-2). The length of the boundary was assigned to approximately correspond to the zones of low salinity areas in the San Andres on the northern and southern end of the Central Basin where discharge from the reef complex is suggested (Figure 7.16, Appendix A-2). The reef complex stratigraphically overlies the San Andres with the Goat Seep, Grayburg and Queen Formations deposited between them, but locally the upper San Andres is part of the lower lateral backreef boundary (Standen et al, 2009). Head-dependant flux boundary cells were assigned only to layers one and two of the model to simulate discharge from the lower portion of the reef complex to the upper portion of the San Andres. Conductances were estimated from the hydraulic conductivity of the San Andres and the reef complex, but were largely determined through calibration.

Heads were assigned to the boundaries according to the condition being simulated. Heads at the boundaries vary from the pre-development condition to the post-development condition and to the geologic past. Heads were assigned based on the pre-development and post-development potentiometric surface maps of Hiss (1975) and were modified as necessary to simulate the geologic past. Heads assigned for the pre-development and post-development condition are summarized in Table 7.4.

Table 7.4. Boundary Heads for the Simulation of the Pre-Development and Post-Development Condition.

Boundary	Pre-Development Head (ft-amsl)	Post-Development Head (ft-amsl)
Eddy-Lea County Boundary	3,300 – 3,570 (south to north)	3,000 – 3,350 (south to north)
Capitan Reef Complex - Southeastern Lea County	3,100	2,150 – 2,600 (south to north)
Lea-Gaines County Boundary	2,900	2,450
Capitan Reef Complex – Northern Pecos County	3,200	2,725 – 2,850 (north to south)
Eastern Pecos County	3,100	3,100

7.3.3. Hydraulic Properties

Hydraulic conductivities (permeabilities) were assigned to the San Andres Artesia Fairway based on the conceptualization of the permeability distribution described in Section 7.2.2.2. The hydraulic conductivity of the porosity zone of the San Andres Artesia Fairway was assumed to be greatest at the center of the permeability trend and decrease by two orders of magnitude at the edges of the Fairway. For simplicity, the width of the Fairway in layer two was divided into three zones of equal width on each side of the centerline of the Fairway. The hydraulic conductivity of each of the zones was increased by a factor of four in Ward and Winkler based on core data from the porosity zone in that area (Trentham, 2011b). An additional hydraulic conductivity zone was assigned to southeastern Lea County and northern Pecos County to represent the zones of enhanced permeability in the San Andres at the northern and southern ends of the Central Basin Platform described by Hiss (1975). This region was given the highest permeability within the Fairway based on pumping test and core data summarized in Section 7.2.2.2.

Permeabilities of the upper and lower San Andres (layer one and three) were assumed to be equal to the permeability of the edge of the porosity zone. The exception is in southeastern Lea and northern Pecos Counties where the zones of enhanced permeability occur in the San Andres. Because most of the wells that draw water from the San Andres in these areas are open to most of the full thickness of the San Andres, the enhanced permeability zones were assumed to extend into the upper and lower San Andres (model layers one and three). Final permeabilities were assigned through calibration (Section 7.3.4).

The vertical permeability of the San Andres was assumed to be one-tenth of the horizontal permeability. Though little information exists to characterize the vertical permeability of the formation, flow through the Fairway is predominantly horizontal such that changes in vertical permeability have little effect on flows. There is also little information available to characterize the storage properties of the San Andres Limestone. Therefore, a typical specific storage coefficient of 5×10^{-7} was assumed.

7.3.4 Model Calibration

The purpose of the model is to simulate flow through the Artesia Fairway in the geologic past when hydrocarbon flushing is theorized to have occurred. However, because little specific information exists to quantify heads and flows in the geologic past, the representativeness of the model was tested by calibration to the current conditions (pre-development and post-development) for which specific observational data is available. The objective of the calibration was to reproduce measured heads and estimated flows from the water budget analysis as closely as possible. However, because of the sparseness and generality of information available for the deep saline portions of the Artesia Fairway, the calibration is conceptual in nature and no specific calibration criteria were specified. A steady-state calibration was performed to the pre-development flow condition, and transient verifications were performed to the post-development flow condition.

7.3.4.1 Pre-Development Calibration

The model was calibrated under steady-state conditions to the heads and flows representative of the pre-development flow condition. Heads used for the steady-state calibration were those used to construct the pre-development potentiometric surface map of Hiss (1975). The heads compiled were from a range of dates and supplemented with heads from other shelf aquifers, but are generally representative of the pre-development heads in the Artesia Fairway (summarized in Figure 7.29 (Appendix A-2) and Appendix C). Because of the sparseness of the head data, the range of dates, and the supplemental use of data from other shelf aquifers, the steady-state calibration was semi-quantitative in nature. Calibration was performed by attempting to minimize residuals (difference between simulated head and measured head), but the heads are only generally representative of the pre-development condition. Given the quality of the pre-development head data, a more rigorous calibration to heads is not warranted. The flows used for the steady-state calibration were those estimated from the water budget analysis of the pre-development condition described in Section 7.2.6.1. Because the water budgets are estimates, the calibration to the flow data is also semi-quantitative in nature.

The model parameters were adjusted as necessary to reproduce to the extent possible the pre-development heads and estimated water budget flows. The modeled flows were evaluated based on the relative difference between the estimated water budget flows and the simulated water budget flows. The modeled heads were evaluated based on the residuals. The calibration was performed by minimizing the model error and the differences between the simulated and conceptual water budgets.

Three statistical measures of model error were utilized to evaluate the steady-state calibration. These are the mean error (ME), absolute mean error (AME), and the root mean square error (RMSE), which provide the following information about the model error:

- ME – indicates whether and to what degree the model is under or over-simulating measured heads.
- AME – quantifies how closely simulated groundwater elevations are to measured elevations
- RMSE – measures the spread of the residuals around the mean value.

Model hydraulic conductivities and boundary conductances were adjusted until the model reasonably reproduced the pre-development heads and flows. Minor adjustments in boundary heads were also made where there was a lack of head data and when necessary to better reproduce flows. The final permeabilities for the calibrated model are shown on Figures 7.30 and 7.31 (Appendix A-2). The permeabilities were largely assigned based on core data (Trentham, 2011b), published values, and the conceptualized relative permeability distribution and modified slightly to improve calibration. The pattern in the permeabilities assigned to the model corresponds to that discussed in Section 7.3.3. Permeabilities in the porosity zone of the San Andres (model layer 2) ranges from 0.4 to 40 mD (edge to center of Fairway) in Ward and Winkler County and from 0.1 to 10 mD (edge to center of Fairway in western Lea and eastern Pecos Counties. The permeability of the enhanced permeability zone in the San Andres in southern Lea and northern Pecos Counties is 100 mD. The permeabilities of the upper and lower San Andres (model layers one and three) are 0.1 mD with the exception of the enhanced permeability zones in southern Lea and northern Pecos Counties.

The simulated pre-development potentiometric surface following calibration is shown on Figure 7.32 (Appendix A-2). The simulated potentiometric surface for layer two is shown, but the potentiometric surfaces for all layers were nearly identical. The error statistics for the calibrated model are provided in Appendix C and are depicted graphically on Figure 7.33 (Appendix A-2). The ME was -17.8 feet, the AME was 59.8 feet, and the RMS error was 83.9 feet. The model reproduced heads along the center of the Fairway relatively well (within 50 feet), but overall, the model somewhat over-simulated heads (simulated heads are too high). This is largely result of the component of the hydraulic gradient that is perpendicular to the long axis of the Fairway. The model cannot reproduce this perpendicular component of the gradient because the adjacent formations were simulated as no flow boundaries. The perpendicular component of the gradient in these areas is not simulated because flows in the perpendicular direction are minimal as a result of the low permeabilities of the adjacent formations. The perpendicular gradient causes the down-gradient heads along the edge of the Fairway to be over-simulated. This is most apparent at the southern edge of the Fairway on the Northwest Shelf in western Lea County where a component of the gradient is southward and in eastern Ward and Winkler County where a component of the gradient is eastward (Figure 7.33, Appendix A-2).

The model under-simulates heads in eastern Lea County near the head dependant flux boundary representing outflow into Gaines County and the Midland Basin (Figure 7.33, Appendix A-2). The pre-development potentiometric surface map of Hiss (1975) shows a relatively flat gradient in this region. A greater hydraulic gradient is required in this region to reproduce the flows estimated from the pre-development water budget analysis. Therefore, a steeper hydraulic gradient was introduced in this region to better represent flows at the expense of reproducing heads. The under-simulated heads in eastern Lea County and the over-simulated heads at the edges of the Fairway account for the majority of the error in the model. The RMSE error over the range of simulated heads in the model was approximately 14 percent. This indicates that approximately 14 percent of the model response is a result of error. Given the generality and sparseness of the head data available for calibration, a lesser model error was not reasonably expected.

The simulated water budget is shown on Table 7.5 along with the conceptual water budget from Section 7.2.6.1. Most of the simulated water budgets were within 20 percent of the conceptual water budget indicating a reasonably good representation of the flow regime. The differences in the simulated water budgets are within the range of uncertainty in the conceptualized water budget.

Similar to the conceptualized system, the greatest inflow to the Fairway was discharge from the Capitan Reef Complex in southeastern Lea County (228 gpm). This flow merged with flow moving eastward along the Northwest Shelf (13 gpm) and exited the Fairway into Gaines

Table7.5. Simulated Pre-Development Water Budget

Boundary	Flow Direction	Conceptual Flow (gpm)	Simulated Flow (gpm)
Eddy-Lea County Boundary	Inflow	1.2 gpm	13 gpm
Capitan Reef Complex -	Inflow	280 gpm	228 gpm
Lea-Gaines County Boundary	Outflow	281 gpm	243 gpm
Capitan Reef Complex – Northern	Inflow	<1 gpm	3.0 gpm
Eastern Pecos County	Outflow	<1 gpm	0.7 gpm

County and the Midland Basin. The model also suggests that pre-development flow through the Fairway in Ward and Winkler County is northward and combines with discharge from the reef complex in southeastern Lea County and flow moving eastward through the Fairway along the Northwest Shelf before discharging out of the Fairway into Gaines County. Though only a small amount of simulated discharge from the reef complex occurred in northern Pecos County (3.0 gpm), the heads in the reef complex at this discharge point are higher than those at the southeastern Lea County discharge point causing the gradient through the Fairway to be northward. Simulated flow through the Fairway in Ward and Winkler County was approximately 2.3 gpm, and the total simulated flow into Gaines County was approximately 243 gpm. Simulated flow also moved eastward away from the northern Pecos County discharge point into eastern Pecos County. The amount of flow is small (0.7 gpm) because the Artesia permeability trend ends to the east.

A comparison was also made between the simulated gradients from the model and the hydraulic gradients implied from the oil/water contact tilts from San Andres oil fields on the northwest shelf (Slaughter Trend) and the east side of central basin platform. As discussed in

Section 7.2.1.3, the tilts of the oil/water contacts in the San Andres are generally consistent with the magnitude and direction of the modern (pre-development) hydraulic gradient (Brown, 2001). The hydraulic gradient that produced the oil/water contact can be calculated from the fluid densities of the water and the oil. The gradients estimated from the various San Andres oil fields with tilted oil/water contacts are depicted on Figure 7.34 (Appendix A-2). The simulated pre-development hydraulic gradients are also depicted.

The simulated gradient through the Fairway along the Northwest Shelf in western Lea County was approximately 18 feet/mile. This is generally consistent with the calculated gradients from the San Andres oil fields to the north in the Slaughter Trend in northern Lea and southern Roosevelt Counties (10 to 28 feet/mile). The simulated gradient in eastern Lea County is approximately 5.5 feet/mile. This is generally consistent with the calculated gradients from the San Andres oil fields further to the east in Gaines, Yoakum, and Terry Counties (5 to 9 feet/mile). The simulated gradients (and flow directions) through Ward and Winkler Counties are not consistent with the calculated gradients for the San Andres oil fields on the east side of the Central Basin Platform, but this is a result of the gradients in Ward and Winkler Counties being influenced by the Capitan Reef Complex, whereas the gradients on the east side of the Central Basin Platform are not. The general consistency of the simulated gradients to the calculated gradients from the San Andres oil fields in the Slaughter Trend on the Northwest Shelf and on the north end of the Central Basin Platform provides an additional line of evidence that the gradients are reasonable.

7.3.4.2. Post-Development Verification

Two post-development simulations were performed to test the reasonableness of the model under pumping stress. The first was the simulation of a water flood supply well field in southeastern Lea County and the second was the simulation of a series of irrigation and water flood supply wells in northern Pecos County (Section 7.2.4.2). These were selected to test whether the model could reasonably be expected to supply the large quantities of water that were being withdrawn from these well fields. Excluding the freshwater zones of the San Andres west of the Pecos River, other areas of the Artesia Fairway are generally not used for water supply.

7.3.4.2.1 Southeastern Lea County

The first post-development verification simulation performed was of the Eunice-Monument water flood supply well field in southeastern Lea County (Figure 7.20, Appendix A-2)). The well field supplied a water flooding operation in overlying Grayburg Formation. Records indicate that six of the wells were installed for the water flooding operation between 1985 and 1987. Two additional wells were installed further to the south between 1992 and 1994. Pumping records were obtained and tabulated for each of the wells (Petroleum Recovery Research Center, 2011) and are summarized in Appendix D. The pumping records date back to 1995, so it was necessary to estimate flows prior to this date. Pumping was assumed to be equal to the 1995 flow rate extending back to the one year following the installation date. The total estimated withdrawal from the wells under these assumptions was approximately 18,000 million gallons (1986 to 2010).

Prior to simulating flow from the supply wells, it was necessary to simulate an initial condition representative of conditions when the wells first began to operate. The post-development potentiometric surface of Hiss (1975) was assumed to be approximately representative of this condition. Heads at the boundaries of the model were adjusted to reflect these post-development heads (Table 7.4).

Static (non-pumping) water levels were available for several of the Eunice-Monument supply wells at the time of their installation. The static water levels ranged from 2,319 to 2,587 feet amsl. These levels were somewhat lower than the post-development heads depicted in the nearby Capitan Reef Complex by the Hiss (1975) post-development potentiometric surface map (Figure 7.17, Appendix A-2). The heads were more similar to a later map of heads in the New Mexico portion of the reef complex developed by Richey et al. (1985). This map depicts heads in the reef complex that are 100 to 300 feet lower in southeastern Lea County. Heads in the reef complex likely had declined in southeastern Lea County between the dates the two maps were constructed. The more recent map is more similar in date to the start-up of the water flood supply well field, and the heads are likely more representative of the heads in southeastern Lea County at that time. Therefore, heads at the boundary in southeastern Lea County representing the reef complex were assigned based on the map by Richey et al. (1985).

A steady-state model simulation was performed to generate the initial heads for the transient simulation of the water flood supply well field. The heads (Figure 7.35, Appendix A-2) and water budgets from the model run were also evaluated to further assess the behavior of flows through the Fairway. The post-development simulation showed a steeper gradient (approximately 30 feet/mile) though the Fairway along the Northwest Shelf than the pre-development simulation as a result of the decline in heads associated with extraction from oil and gas fields and water flood supply well fields. The result is an increased flow entering from the specified head boundary assigned to the flow divide at the Eddy-Lea County boundary (21 gpm). In southeastern Lea County, gradients are more toward the southeast as compared to the pre-development simulation, and contours are roughly parallel to the trend of the Capitan Reef Complex. Because flow is generally parallel to the head dependant flux boundary representing the reef complex, the flow across the boundary is minimal. Simulated flows across the boundary are into the Fairway at the northwestern end of the boundary (where heads in the reef complex are higher) and out of the Fairway at the southeastern end of the boundary (where heads in the reef complex are lower). The net simulated flow across the boundary is approximately zero. The post-development simulation suggests that withdrawals from Capitan Reef Complex centered in Ward and northern Winkler County have largely halted natural discharge from the reef complex to the San Andres. Because discharge from the reef complex is greatly reduced, flow out of the Fairway into Gaines County and the Midland Basin is also greatly reduced (32 gpm).

Flow moving northward along the Fairway in Ward and Winkler County was greater (11 gpm) for the post-development simulation relative to the pre-development simulation as a result of steeper gradients through the area (Figure 7.35, Appendix A-2). Discharge from the reef complex in northern Pecos County was also similarly increased (9 gpm). The simulation suggested that flow in eastern Pecos County would be reversed toward the west under the post-development condition, but no reliable head data were available for this portion of the Fairway. The reversal may be an artifact of the uncertainty in the head assigned to the head dependant flux boundary at the end of the Artesia permeability trend. The heads were assumed to be equal to the pre-development head on account of the lack of data. A comparison of the conceptual water budget and the simulated water budget for the post-development flow condition is provided on Table 7.6. All simulated flows are considered to be order-of-magnitude estimates since the local influence of withdrawal and injection is not considered in the simulations.

Table 7.6. Simulated Post-Development Water Budget

Boundary	Flow Direction	Conceptual Flow (gpm)	Simulated Flow (gpm)
Eddy-Lea County Boundary	Inflow	2 gpm	21 gpm
Capitan Reef Complex -	Inflow	0 - 20 gpm	0 gpm
Lea-Gaines County Boundary	Outflow	2 - 22 gpm	32 gpm
Capitan Reef Complex – Northern	Inflow	variable	9 gpm
Eastern Pecos County	Outflow	<1 gpm	2 gpm (inflow)

The steady-state post-development simulation was used as the initial condition for the transient simulation of the water flood supply wells. The transient simulation was set up with 25 one-year long stress periods representing the time period between 1986 and 2010 (inclusive). Annual pumping stresses for the supply wells (Appendix D) were then input into the model. The model was then run forward and the drawdowns produced by the pumping were evaluated.

No pumping water level data were available for the water flood supply wells to use to compare with the heads from the transient simulation. Therefore, verification was performed in a more general manner in which it was ascertained whether the large amount of water withdrawn by the supply wells could be sustained by the model without utilizing more than one-half of the drawdown available to the wells. Given the lack of available operational data, one-half of the available drawdown was assumed to be a reasonable maximum operational limit. The available drawdown is defined as the difference between the static water level and top of the open-hole interval of the well (bottom of casing). The minimum available drawdown for the wells was 2,838 feet and the maximum was 3,350 feet.

Maximum annual pumping from the supply wells likely occurred in 1995 (the first year for which pumping data were available) when total withdrawals reached 3,192 gpm. Pumping gradually declined since 1995 and decreased to approximately 164 gpm in 2010. Drawdowns from the model simulation increased until the 1995 maximum pumping year and then recovered in response to the declining pumping that occurred thereafter. The maximum drawdown reached approximately 1,330 feet at well CP 00693 (Figure 7.36, Appendix A-2). This represents approximately 47 percent of the total available drawdown and suggests that model could reasonably sustain pumping from the supply wells.

The water budgets from the simulation were also evaluated to determine whether the quantities of flow being drawn to the supply wells are reasonable. Of particular interest was the year 1995 stress period when simulated pumping from the supply wells was greatest. This stress period demonstrates the maximum effect of pumping on the Artesia Fairway. Water budgets at the flow divide at the Eddy-Lea County boundary and at southern end of the Fairway are largely unaffected by pumping from the supply wells, indicating that these areas are not a source of water to the supply wells. The changes in simulated flow occurred primarily at the head-dependant flux boundary representing outflow from the Fairway into Gaines County and the head dependant flux boundary representing the Capitan Reef

Complex. The flow direction at the boundary representing outflow into Gaines County was reversed with flow converging toward the supply wells. The post-development outflow of approximately 34 gpm without any pumping at the supply wells became an inflow of approximately 9 gpm during the maximum pumping year. This suggests the supply wells captured water that otherwise would have discharged into Gaines County, and this captured flow is a source of water to the supply wells.

A large change in the water budget occurred at the boundary representing the Capitan Reef Complex. A simulated inflow of 1,108 gpm (35 percent of total 1995 pumping) occurred during the maximum pumping year, suggesting that induced inflow from the reef complex represents a large portion of the source water to the supply wells. However, the simulations suggest that the greatest source of water to the supply wells is from storage release from the San Andres Formation in the Artesia Fairway. The simulations indicated a total storage release of 11,600 million gallons over time the supply wells were operational (approximately 64 percent of the total quantity of water pumped).

The steady-state post-development simulation suggested that natural discharge from the reef complex into the San Andres Artesia Fairway ceased during post-development times as a result of pumping from water flood supply well fields in the reef complex to the south. The source of inflow from the reef complex and to the San Andres water flood supply wells must therefore be from aquifer storage release. Assuming the total estimated pumping from the supply wells of 18,300 million gallons, subtracting the storage release from the San Andres (11,600 million gallons), and the smaller amount of water flowing though the Fairway that was captured by the wells (500 million gallons), approximately 6,200 million gallons of water released from storage would be required from the reef complex. Assuming a confined storativity of 0.0001 and an unconfined storage coefficient of 0.01, an average drawdown of approximately 15 feet would be required across the entire reef complex from Lea County to the outcropping in the Glass Mountains. The largest release from storage would occur in the unconfined portions of the reef complex near the Glass Mountains due to the higher storage coefficients in this area. It is also possible that some water could come from the vicinity of the Pecos River to the west if drawdowns were sufficient to remove the groundwater flow divide near the Eddy-Lea County boundary. Given the large scale withdrawals from the well fields in the reef complex and the hundreds of feet of drawdown that has occurred during post-development times (including in the unconfined areas of the reef complex near the Glass Mountains), the required storage release from the reef complex would appear to be reasonable. Simulated drawdown near the model boundary representing the reef complex was greater than 80 feet during the maximum pumping year.

7.3.4.2.2. Northern Pecos County

The San Andres irrigation and water flood supply wells in northern Pecos County were also simulated to test the reasonableness of the model under pumping stress (Figure 7.21, Appendix A-2). Information related to the wells is summarized in the Armstrong and McMillion (1961) study and are summarized in Appendix E. A total of 33 San Andres wells were identified in northern Pecos County with 22 listed as active at the time of the study. The first recorded well installation date was in 1926, but the majority of the wells were installed in the late 1940s and early 1950s. One-time flow measurements from the wells were compiled during the study with measurement dates ranging from 1947 to 1957. Measured flow rates ranged from 5 to 3,500 gpm with an average of approximately 900 gpm. All wells were under artesian pressure and flowing at the time of installation.

Little water usage data were available for the time period of the Armstrong and McMillion (1961) study; however, the study estimated that 6,200 gpm of water from the San Andres water was produced in 1957. Water level data for the wells was also lacking, but because wells were simply allowed to flow when in use, a water level equal to that of ground surface could be assumed. Ground surface is typically around 700 feet below the estimated pre-development potentiometric surface, which explains the strong artesian heads in the region.

A transient simulation was performed to evaluate whether the model could reasonably provide flows in the range of the estimated 1957 total usage rates for the wells in northern Pecos County (6,200 gpm). Because actual periods of use and non-use are not known for the wells, it was assumed that those identified as active in the Armstrong and McMillion (1961) study were active for the entire duration of the simulation. Those listed as inactive were not simulated. The simulation was performed for a period of ten years, which corresponds to the period between the median installation date of 1947 (for wells with recorded installation dates) and the year for which estimated usage rates are available (1957).

Similar to the southeastern Lea County simulations, the transient simulation of the northern Pecos County wells requires the initial condition to be defined. Because the time period that the northern Pecos County wells were being installed dates back to when development of the region was just beginning, the pre-development condition was assumed as the initial condition for the simulation.

The northern Pecos County wells were simulated using drain cells. Drain cells allow water to be discharged from the model in proportion to the head difference between model cell and the drain cell. Discharge from the drain cells is also proportional to the assigned conductance, but very large conductance values were assigned to the cells so that the conductance provided no limitation of flow into the cells. The heads assigned to the drain cells were equal to the ground surface at the wells. The head values were held constant through the simulation and the model was allowed to calculate the flow required to produce the given head value. The simulation was divided into 40 time steps with approximately 3 months represented per time step. Flows were calculated for the end of each time step.

The drain cells were allowed to remain active through the entire duration of the simulation, which would be representative of a continuously flowing artesian well. Though this does not accurately simulate the actual usage of the wells unless the water is allowed to continuously flow (i.e. most wells were likely shut-in when not in use), the simulation nevertheless provides a general representation of the behavior of the wells and the aquifer.

The water budgets from the simulation were evaluated to determine how much flow the simulated wells in northern Pecos County could reasonably be expected to produce. The primary sources of water to the wells were also evaluated. The water budgets showed that flow rates to drain cells were initially very high prior to significant depletion of storage in the San Andres and gradually declined through the simulation as storage becomes depleted. Initial total discharge from the drains (end of the first time step) was on the order of 17,000 gpm with individual well flow rates ranging up to over 1,000 gpm. The source of water during the initial period was almost entirely from storage. Within the first year, the discharge from drains declined to approximately 6,500 gpm and by the end of the ten year simulation the discharge rates declined to approximately 3,000 gpm. The simulations suggest that although the high flow rates from the San Andres wells recorded in 1957 are probably not sustainable in the long-term, high initial flow rates are possible due to the large amount of storage initially available to the wells. Sustainable flow rates would continue to decline beyond the ten-year simulation until a steady state condition would eventually be achieved. Though information is lacking for most of the northern Pecos County wells, several of the wells were reported to have stopped flowing at some period following installation (Armstrong and McMillion, 1961). Head in another well was reported to have declined the equivalent of 160 feet (estimated from well pressure measurements) in six years. These data are reflective of the depletion in storage from the San Andres similar to that shown in the model simulation.

As storage became depleted during the model simulation, the source of water to wells gradually changed. Simulated flows at the northern end of the model domain (Winkler, Lea, and Eddy Counties) and simulated flows from the head dependant flux boundary in eastern Pecos County were unchanged from the pre-development simulation, indicating that these areas are not a significant source of water to the wells. The primary source of water excluding storage was the head dependant flux boundary in northern Pecos County representing the Capitan Reef Complex. Initial simulated inflows across the boundary were very small, but accounted for approximately two-thirds of the total water discharged by the drain cells at the end of the ten-year simulation. The ultimate source of this water is likely storage from the reef complex, especially from the nearby unconfined portion of the complex near the Glass Mountains. The simulated drawdowns at the end of the ten-year simulation are depicted on Figure 7.37 (Appendix A-2).

The southeastern Lea County and northern Pecos County transient simulations demonstrated that the groundwater flow model could reasonably be expected to produce the quantity of water being withdrawn from the Artesia Fairway in these areas. Though data required for a more involved calibration were lacking, the simulations suggest that the model is capable of generally simulating flow through the Artesia Fairway under both non-pumping and pumping conditions. The calibrated model provided the basis for performing simulations of the geologic past when flushing of hydrocarbons is theorized to have occurred. The development of these simulations is described in the following Section 8.0.

7.3.5 Sensitivity Analysis

After calibration of the model was completed, a sensitivity analysis was performed to evaluate and quantify the influence of changes in uncertain model parameters on the response of model; specifically, the flows through the Fairway in Ward and Winkler Counties. The parameters evaluated were the most uncertain parameters in the model evaluation and included the permeabilities of the Fairway and the conductances of the model boundaries. These parameters were varied within reasonable ranges and the resulting change in the simulated flows through Ward and Winkler Counties were tabulated. Results from the sensitivity analysis are depicted graphically in Appendix F.

7.3.5.1 Permeability

The sensitivity of the model to changes in permeability was evaluated by increasing and decreasing the permeability values in the model within reasonable ranges. Both the sensitivity of the model to changes in the permeability in Ward and Winkler Counties alone and to changes in the permeability of the entire Fairway were evaluated.

Within Ward and Winkler Counties, the maximum permeability in the calibrated model is 40 mD at the center of the Fairway within the porosity zone (model layer 2). Based on core data, reasonable ranges for the maximum permeability zone range from 10 mD to 100 mD (Trentham, 2011b). This represents a relative change ranging from 25 percent to 250 percent of the calibrated value. To evaluate the sensitivity of the model to changes in the permeability of Ward and Winkler Counties, all of the modeled permeability zones in Ward and Winkler Counties (i.e. the zones between the two zones of enhanced permeability in southeastern Lea and northern Pecos Counties) were adjusted within this range of percentages simultaneously. This included the modeled permeabilities of the upper and lower San Andres (model layer 1 and 3) in Ward and Winkler Counties.

The change in simulated flows through the Fairway in Ward and Winkler Counties resulting from change in the permeability of the Fairway in Ward in Winkler Counties is depicted on Figure F1 (Appendix F). The figure shows that the simulated flow in Ward and Winkler County is highly sensitive to changes in the permeability in Ward and Winkler County and that the change in simulated flow is approximately directly proportional to the change in permeability. A given percent increase or decrease in the permeability results in a similar percent increase or decrease in the simulated flow. The simulated gradients through the Fairway across Ward and Winkler Counties changed little for the individual sensitivity simulations such that the simulated flow through Ward and Winkler Counties was controlled predominantly by the change in permeabilities.

The sensitivity of the model to changes in permeabilities of the entire Fairway was evaluated by adjusting all of the modeled permeability zones within the Fairway from 25 percent to 250 percent. The exception was the two zones of enhanced permeability in southeastern Lea County and northern Pecos County. The modeled permeability in these zones (100 mD) is near the upper of the range of measured permeabilities for the San Andres Formation and further increases would likely be unreasonable. The permeability in these zones was held constant for sensitivity simulations.

The change in simulated flows through the Fairway in Ward and Winkler Counties resulting from the change in the permeabilities of the entire Fairway (excluding the enhanced permeability zones in southeastern Lea and northern Pecos Counties) is depicted on Figure F2 (Appendix F). The change in simulated flows was nearly identical to those exhibited by the sensitivity analysis to changes in the permeability in Ward and Winkler Counties alone. Similar to the changing the permeabilities within Ward and Winkler County alone, changing the permeabilities over the entire Fairway (excluding the enhanced permeability zones in southeastern Lea and northern Pecos Counties) had little effect on the gradients within Ward and Winkler County, and the simulated flow through Ward and Winkler Counties was predominantly controlled by the change in permeability in Ward and Winkler County.

7.3.5.2 Boundary Conductance

The sensitivity of the model to the conductances assigned to the head-dependant flux boundaries representing inflow or outflow to the model was also evaluated. The head-dependant flux boundaries representing the San Andres Formation and the Capitan Reef Complex were considered separately. The conductances of the model boundaries are related to the permeability of the formation being represented. Similar to the sensitivity analysis to the modeled permeabilities, the boundary conductances were adjusted within a range of 25 percent and 250 percent of the calibrated value.

The head-dependant flux boundaries representing the San Andres Formation include the model boundary at Lea-Gaines County boundary and the model boundary at the end of the Fairway in eastern Pecos County. The conductances of these two boundaries were adjusted simultaneously. The resulting simulated flows through Ward and Winkler Counties are depicted on Figure F3 (Appendix F). The change in the conductance of the San Andres boundaries had little to no effect on the simulated gradients across the Fairway in Ward and Winkler County. Consequently, there was also little to no effect on simulated flows through Ward and Winkler County. The analysis indicates that the model is insensitive to the conductances of the San Andres head-dependant flux boundaries.

The head-dependant flux boundaries representing the Capitan Reef Complex include the lateral model boundaries in southeastern Lea County and northern Pecos Counties. The simulated flows through the Fairway in Ward and Winkler County resulting from changes to the conductances of the Capitan Reef Complex head-dependant flux boundaries are depicted on Figure F4 (Appendix F). The figure shows that the simulated flows through the Fairway in Ward and Winkler Counties are somewhat sensitive to conductance of the reef complex, but mostly at the low end of the conductance range. As the conductance is decreased, flow discharging to the Fairway from the reef complex in southeastern Lea County becomes reduced, resulting in a decrease in simulated heads in the Fairway around the boundary. The decline in heads increases the simulated hydraulic gradients across Ward and Winkler Counties, which increases the simulated flow (up to approximately 9 percent). The source of the additional water is the boundary representing the reef complex in northern Pecos County. Despite the decrease in conductance in this boundary, simulated inflow from the boundary increases slightly in response to the increased hydraulic gradient. This sensitivity evaluation also implies that the heads in the reef complex at the discharge boundaries in southeastern Lea and northern Pecos Counties are the primary factor controlling the gradients in the Fairway through Ward and Winkler Counties, and the model will be sensitive to changes in parameters that influence these heads.

7.3.5.3 Sensitivity Summary

The sensitivity analysis indicates that the simulated flow through Ward and Winkler Counties is controlled by the permeability of the Fairway in Ward and Winkler Counties and the simulated gradient through the Fairway in Ward and Winkler Counties. The gradient through the Fairway in Ward and Winkler Counties is largely controlled by the heads in the reef complex at the discharge boundaries in southeastern Lea and northern Pecos Counties and the model is sensitive to changes in parameters that influence these heads (i.e. the conductance of the reef complex boundaries).

8.0 MODEL SIMULATIONS

Following calibration of the groundwater flow model, the model was used to simulate the geologic past. The conceptualized flow system of the geologic past was simulated predominantly by modifying the boundary conditions within the model. The hydraulic properties (permeabilities) of the model that were established through the calibration of the model to the pre-development and post-development condition were assumed to also be representative of the geologic past. The conditions assumed to simulated the geologic past and the results of the simulations are described in the following sections.

8.1 Simulation of the Geologic Past

Flow through the Artesia Fairway along the Northwest Shelf was greater during the geologic past as a result of increased land elevations to the west of the Guadalupe Mountains and along the western uplifted rim of the Sacramento Mountains, the wetter climate, and the lack of a discharge outlet to the Pecos River. These conditions were expressed as a steeper hydraulic gradient within the Artesia Fairway along the Northwest Shelf. The head at the Eddy-Lea County Boundary was estimated to be 4,043 feet-amsl assuming linear slope in heads between the current high points in the San Andres Formation in the Sacramento Mountains and the western edge of the high permeability zone of the San Andres in southeastern Lea County. This estimated head was assigned to the specified head boundary cells in the model at the Eddy-Lea County boundary to reproduce the gradients across the Northwest Shelf. The heads at the specified head boundary representing outflow from the Fairway into Gaines County and the Midland Basin were assumed to be unchanged in the geologic past relative to the pre-development condition.

At the southern end of the Artesia Fairway, the theorized discharge points associated with the sulfur mines in Pecos County were added to the model. The discharge points were simulated with drain cells centered on each of the sulfur deposits (Figure 7.9). The sulfur deposits extend upward to the base of the Rustler Formation, and the discharge of water at locations of the sulfur deposits was likely into the Rustler Formation laterally to the east and eventually to the surface, either locally or at a distance. The presence of a discharge pathway at the southern end of the Artesia Fairway would have lowered heads in this region. Heads assigned to the drain cells representing the discharge points from the Artesia Fairway were assumed to be equal to ground surface to represent the lowering of the potentiometric surface around the discharge points. Actual heads may have been higher or lower depending on the actual exit point.

Heads in the Capitan Reef Complex would also have been different during the geologic past. Heads along the Northwest Shelf would have been higher because of the increased flow resulting from the absence of the discharge point to the Pecos River. At the southern end of the reef complex, heads would likely also have been higher near the Glass Mountains because of the wetter climate and increased recharge in this region. However, in northern Pecos County near the discharge boundary with the San Andres Formation, heads in the reef complex would likely have been lower because of the nearby discharge pathway in the San Andres Fairway represented by the sulfur deposits.

The exact heads in the reef complex during the geologic past are largely a matter of speculation. Because the heads in the reef complex are not well understood, the heads at the model boundaries representing the reef complex were estimated by iterative adjustment of the heads in the model. The heads were iteratively adjusted until the simulated discharge from the reef complex approximately balanced conceptualized inflows to the reef complex as described in the water budget analysis of the geologic past (Section 7.2.6.3).

From the water budget analysis, it was estimated that approximately 560 gpm of water was flowing eastward along the northwest shelf and approximately 660 gpm of water was flowing northward from the recharge area in the Glass Mountains. Based on iterative adjustment of the boundary heads, heads of 3,050 feet amsl at the southeastern Lea County boundary and 2,800 feet in northern Pecos County provided the best match between the conceptualized flow in reef complex and the simulated discharge to the San Andres and the Artesia Group.

The significance of the estimated boundary heads is that flow through the reef complex may have been north to south during the geologic past rather than south to north as simulated during the pre-development condition (Figure 8.1, Appendix A-2). The north to south flow would primarily have been the result of the absence of the connection to the Pecos River along the northern limb of the reef complex and the existence of a discharge pathway in the San Andres in northern Pecos County. Of the estimated 560 gpm moving through the northern reef complex, the model simulations produced an inflow into the San Andres Fairway in southeastern Lea County of 168 gpm. Assuming that 15 percent of the total discharge from the reef complex flows into the Artesia Group (as estimated in Section 7.2.6.1), an additional 25 gpm of water from the reef complex would have been discharging into the Artesia Group in southeastern Lea County.

Based on the hydraulic properties and hydraulic gradients in the reef complex between the southeastern Lea County and northern Pecos County model boundaries, an estimated 404 gpm of water would have moved southward through the reef complex through Ward and Winkler Counties. In northern Pecos County, flow moving northward from the Glass Mountain recharge area (estimated 660 gpm) combines with flow moving southward through the reef complex in Ward and Winkler County (404 gpm) and discharges into the San Andres and the Artesia Group. Simulated inflow into the San Andres Artesia Fairway was 882 gpm. Assuming 15 percent of the total discharge from the reef complex in northern Pecos County discharges to Artesia Group, an additional 132 gpm would have discharged from the reef complex into the Artesia Group in northern Pecos County. The combined discharge from the reef complex is approximately equivalent (within 10 percent) to the combined estimated inflows to the reef complex.

Simulated inflow into the Fairway at the Eddy-Lea County Boundary from the unbroken land mass to the west was 32 gpm. The simulated inflow was approximately 2.5 times the simulated inflow from the pre-development simulation. This water combined with a portion of the discharge from the reef complex in southeastern Lea County and exited into Gaines County and the Midland Basin. Total simulated discharge into Gaines County was 194 gpm. All of the water moving through the Fairway along the Northwest Shelf discharged into Gaines County, and none moved southward into Ward and Winkler County. The source of water to Ward and Winkler County was the northern limb of the reef complex. The simulated gradient through Ward and Winkler County was 6.1 feet/mile. The flow rate through Ward and Winkler County was 6.3 gpm. Flow moving southward through the Fairway in Ward and Winkler

Table 8.1. Simulated Water Budgets of the Geologic Past

Boundary	Flow Direction	Quantity (gpm)
Eddy-Lea County Boundary	Inflow	32 gpm
Capitan Reef Complex - Southeastern Lea County	Inflow	168 gpm
Lea-Gaines County Boundary	Outflow	194 gpm
Capitan Reef Complex – Northern Pecos County	Inflow	882 gpm
Discharge Points Represented by Sulfur	Outflow	891 gpm
Eastern Pecos County	Inflow	3.1 gpm

traveled to the discharge points in the San Andres in northern Pecos County represented by the sulfur mine locations. The water from Ward and Winkler County combined with water discharge from the reef complex in northern Pecos County to provide a total discharge of 891 gpm at the sulfur deposit locations. The simulated water budget for the geologic past is summarized in Table 8.1.

The simulated groundwater flow velocity through the Artesia Fairway in Ward and Winkler County in the geologic past was also estimated from the model. Because groundwater velocity is proportional to the permeability of the formation, the velocities were different for each permeability zone of the Artesia Fairway assigned to the model (Figures 7.30 and 7.31, Appendix A-2). Groundwater flow velocity is also proportional to the porosity (n) of the formation. Porosities of the San Andres were assumed to range from 6 percent to 16 percent with an average porosity of 10 percent (Summers, 1972). A range of velocities for each permeability zone was obtained from the model using the low range, average, and high range porosities. The ranges of simulated velocities are summarized in Table 8.2.

The number of pore volume flushes that have occurred through the Artesia Fairway in Ward and Winkler County in the geologic past was also estimated using the model to determine if sufficient flushing of the Fairway could have occurred to reduce hydrocarbon accumulations to residual saturation. The pore volume calculations were performed for the permeability zone at the center zone of the porosity zone (layer two) of the Fairway in Ward and Winkler County (Figure 7.30, Appendix A-2). Most of the flushing through the Fairway would have occurred

Table 8.2. Simulated Groundwater Flow Velocities in the Geologic Past

Conductivity Zone	Velocity (n = 6%) (ft/1,000 years)	Velocity (n = 10%) (ft/1,000 years)	Velocity (n = 16%) (ft/1,000 years)
Layer One	1.9	1.1	0.7
Layer Two – Center Zone	738	446	278
Layer Two – Intermediate Zone	72	44	27
Layer Two – Edge Zone	7.2	4.3	2.7
Layer Three	1.9	1.1	0.7

Table 8.3. Simulated Number of Pore Flushes in the Geologic Past

	n = 6%	n = 10%	n = 16%
Total Pore Volume (ft^3)	1.22×10^{11}	2.04×10^{11}	3.26×10^{11}
Flow Rate (ft^3/day)	1,030		
Time Period (Million Years)	15		
Total Flow (cubic feet)	5.64×10^{12}		
Number of Pore Flushes	46.0	27.7	17.3

through this zone. The total pore volume was estimated by calculating the average thickness of the center zone of the porosity zone in layer two of the model, multiplying by the horizontal extent of the zone, and multiplying by the estimated porosity. The calculation was performed for the low range, average, and high range porosities described above. The total estimated pore volume ranged from 122 to 326 billion cubic feet (Table 8.3).

The total flow volume through center zone of the porosity zone of the Fairway was calculated by taking the simulated flow rate through the center zone (5.35 gpm) and multiplying by the time period over which most of the flushing was assumed to have occurred. Assuming most of the flushing occurred in the late Oligocene and early Miocene, the time period of interest is approximately 15 million years. The total flow volume that would have occurred over 15 million years at 5.35 gpm is 5,642 billion cubic feet. The number of pore flushes that would result ranges from 17 for the high range porosity to 46 for the low range porosity (Table 8.3). This is how much compared to usual commercial waterflood?

8.2 Parameter Sensitivity

Similar to the sensitivity analysis of the calibration simulation, a sensitivity analysis of the simulation of the geologic past was performed to evaluate the influence of uncertain parameters on the results of the model. The sensitivity analysis of the geologic past focused on the influence of the uncertain parameters on the simulated flows in Ward and Winkler Counties. This sensitivity analysis is particularly important given the uncertainties involved with simulating the geologic past. Similar to the calibration sensitivity analysis, the sensitivity of the simulation of the geologic past to the permeability of the Fairway in Ward and Winkler County, the permeability of the entire Fairway, and the boundary conductance of the head-dependant flux boundaries representing the San Andres Formation was evaluated. In addition to these parameters, the sensitivity to the simulated heads at constant head boundary at the Eddy-Lea County border that representing flow through the Fairway along the Northwest Shelf was evaluated. These heads were estimated from current high point elevations in the San Andres Formation in the Sacramento Mountains, but there is considerable uncertainty in the actual groundwater elevations along the Northwest Shelf during the geologic past.

In addition to the parameters discussed above, which relate to the San Andres Formation, the sensitivity of the parameters relating to the Capitan Reef Complex was also evaluated. These include the recharge rate estimated for the reef complex in Glass Mountains and the hydraulic conductivity of the reef complex. Because the reef complex was simulated with boundary conditions (head-dependant flux boundaries), the sensitivity analysis of the reef complex parameters was performed in a more conceptual manner (described below). Results from the sensitivity analysis of the simulation of the geologic past are summarized graphically in Appendix G.

8.2.1 Permeability of the Fairway

There is considerable uncertainty in the permeability of the San Andres Formation in the geologic past. Though the model permeability of the Fairway under pre-development and post-development conditions was tested through calibration, the permeability may have been different during the geologic past as a result of formation dissolution and/or pore-infilling process that operate over geologic time frames. The sensitivity analysis of the hydraulic conductivity of the Fairway is intended to evaluate what influences these processes could have had on flows through Ward and Winkler County in the geologic past.

The permeabilities for Ward and Winkler Counties alone and the permeabilities for the entire Fairway (excluding the enhanced permeability zones in southeastern Lea and northern Pecos Counties) were adjusted within the same range of percent change as for the sensitivity analysis of the calibration simulation (25 percent to 250 percent). The changes in the simulated flows in Ward and Winkler Counties resulting from the change in the modeled permeabilities are depicted on Figures G1 and G2 (Appendix G). Though the simulated flow direction and flow rates in Ward and Winkler Counties for the geologic simulation were different than for the calibration simulation, the percent change in flows resulting from similar percent changes in permeability were nearly identical. Similar to the calibration sensitivity analysis, the simulated flow through Ward and Winkler County is approximately directly proportional to the percent change in the permeabilities of both Ward and Winkler County alone and of the entire Fairway. As with the calibration simulation, the change in hydraulic gradient across Ward and Winkler County for the individual sensitivity simulations was minor such that the permeability of Fairway in Ward and Winkler Counties is the primary factor controlling flow.

8.2.2 Conductances of the San Andres Boundaries

The conductances of the San Andres head-dependant flux boundaries representing inflow or outflow into the model are also related to the permeability of the San Andres. The San Andres head-dependant flux boundaries include the boundary at the Eddy-Gaines County border and the boundary at the end of the Fairway in eastern Pecos County. Similar to the sensitivity analysis for permeability, the conductances of the San Andres head-dependant flux boundaries were varied from 25 percent to 250 percent of the conductances from the simulation of the geologic past.

The change in simulated flow in Ward and Winkler Counties resulting from changes in the counductances of the San Andres head-dependant flux boundaries are depicted on Figure G3 (Appendix G). Similar to the sensitivity analysis of the calibration simulation, changes in the conductances of the San Andres head-dependant flux boundaries had little to no influence on the simulated gradients and flows through the Fairway in Ward and Winkler County.

8.2.3 Head at the Eddy-Lea County Boundary

The stratigraphic elevations of the San Andres Fairway to west of the Guadalupe Mountains prior to fault blocking in the middle to late Miocene were estimated from current stratigraphic high-point elevations of the San Andres Formation in the Sacramento Mountains (Pajarito Mountain and Sacramento Canyon). At Pajarito Mountain, the high-point elevations of the San Andres are approximately 8,610 feet-amsl for the top of the formation and 8,220 feet-amsl for the bottom of the formation (Kelley, 1971). At Sacramento Canyon, the high-point elevations are approximately 9,340 ft-amsl for the top of the formation and 8,240 feet-amsl for the bottom of formation (Livingston Associates and John Shomaker and Associates, 2002). The heads in the San Andres at these two locations were assumed to be equal to the mid-point elevation between the top of formation and bottom of formation; however, the potentiometric surface could have theoretically existed at any elevation within the formation (or perhaps higher if confined). Increased or decreased heads at the high-point locations would result in a corresponding increase or decrease in the gradients through the Fairway across the Northwest Shelf. Assuming a linear hydraulic gradient between the top of formation and bottom of formation elevations at Pajarito Mountain and Sacramento Canyon and the groundwater elevation (pre-development) at the western edge of the enhanced hydraulic conductivity zone in the Fairway in southeastern Lea County (3,000 ft-amsl), the gradients across the Northwest Shelf could have ranged from 39.5 to 47.9 feet/mile. The corresponding heads at the Eddy-Lea County boundary could have ranged from 3,928 feet-amsl to 4,124 feet-amsl.

The influence of changes in the hydraulic gradient across the Northwest Shelf on the simulated flow through the Fairway in Ward and Winkler Counties was evaluated by varying the heads at the model boundary at the Eddy-Lea County border between elevations of 3,928 feet-amsl and

4,124 feet-amsl. Because this does not represent a large range in heads and because of the uncertainty of the land elevations west of the Guadalupe Mountains in the geologic past, two additional sensitivity simulations were performed with boundary heads that were 100 feet lower than the low end of the range and 100 feet higher than the high end of the range.

The influence of the changes in simulated head at the Eddy-Lea County boundary is depicted on Figure G4 (Appendix G). Changes in the simulated head at the Eddy-Lea County boundary had little to no influence on the simulated flows through the Fairway in Ward and Winkler County. For all of the sensitivity simulations, simulated flow through the Fairway along the Northwest Shelf exited the model at the head-dependant flux boundary at the Lea-Gaines County border. Since none of the flow moving along the Northwest Shelf traveled to Ward and Winkler counties, the gradient across the Northwest Shelf does not significantly influence the flow through the Fairway in Ward and Winkler Counties.

8.2.4 Recharge to the Capitan Reef Complex

The recharge entering the Capitan Reef Complex in the Glass Mountains during the geologic past was estimated from the flora present in the region during the late Oligocene and early Miocene. The flow moving northward through the reef complex from the Glass Mountains was estimated to be 660 gpm; however, there is considerable uncertainty involved with any estimate of recharge or precipitation in the geologic past. The influence of the uncertainty in the recharge to the reef complex in the Glass Mountains was evaluated by assuming increased and decreased flows moving northward through the reef complex during the geologic past and evaluating the resulting influence on simulated flows through the Fairway in Ward and Winkler Counties. The low-end of the range of flows assumed to be moving northward from the Glass Mountains was assumed to be 330 gpm (equal to the pre-development flow) and the high-end range of flows was assumed to be 990 gpm.
Since the Capitan Reef Complex was simulated with the use of boundary conditions, the sensitivity to the recharge to the reef complex was performed in a more conceptual manner. The heads at the boundaries representing the reef complex (southeastern Lea and northern Pecos Counties) were iteratively adjusted until the conceptualized inflows to the reef complex from the Glass Mountains and the northern limb of the reef complex approximately balanced (within 10 percent) the simulated discharge from the reef complex to the Fairway and the conceptualized discharge to the Artesia Group (similar to simulation of the geologic past, it was assumed that 85 percent of the discharge from the reef complex at the model boundaries would enter the San Andres and 15 percent would enter the Artesia Group). The flow moving through the reef complex between the model boundaries in southeastern Lea and northern Pecos Counties was also considered by calculating this flow based on hydraulic properties of the reef complex and the calculated gradient between the boundaries (assuming heads equal to those assigned to the model boundary). The same method was used to assign the heads for the boundaries representing the reef complex for the geologic simulation (Section 8.1.1).

The influence of the changes in the conceptualized flow moving northward through the reef complex from the Glass Mountains (resulting from changes in the assumed recharge to the reef complex during the geologic past) are summarized in Figure G5 (Appendix G). The heads required at the reef complex boundaries in southeastern Lea and northern Pecos Counties are also depicted. In general, the simulations suggest that increased recharge to the reef complex in the Glass Mountains (and the resulting increased flows northward) would increase heads in the reef complex in northern Pecos County. The simulations also suggest that increased recharge in the Glass Mountains would also increase heads in the reef complex in southeastern Lea County (though to a lesser degree) because of the reduced southward gradients in the reef complex between southeastern Lea and northern Pecos Counties. Decreased recharge would have the opposite effect on both boundaries.

The simulated flows through Ward and Winkler Counties were somewhat sensitive to changes to the conceptualized changes in the flow moving northward through the reef complex from the Glass Mountains. The simulated flows through Ward and Winkler County were sensitive because the heads at the reef complex boundaries influence the simulated gradients through the Fairway in Ward and Winkler Counties. The decreased gradient in the reef complex between the model boundaries in southeastern Lea and northern Pecos Counties that results from increases in recharge to the Glass Mountains causes a similar decrease in the gradient through the Fairway in Ward and Winkler Counties, and correspondingly, decreased flows.

8.2.5 Permeability of the Capitan Reef Complex

Similar to the permeability of the Fairway, the permeability of the Capitan Reef Complex may have been different during the geologic past as a result of formation dissolution and/or pore-infilling processes that occur over geologic time. To evaluate the influence of these processes, a sensitivity analysis was also performed for the permeability of the reef complex.

The sensitivity analysis of the permeability of the reef complex was conceptual in nature similar to the sensitivity analysis of the recharge to the reef complex in the Glass Mountains. The influence of higher or lower permeabilities would primarily be a change in the quantity of water moving eastward through the reef complex at the Laguna submarine canyon restriction point along the northern limb of the reef complex and the quantity of flow moving through the reef complex between the southeastern Lea and northern Pecos County model boundaries (for a given hydraulic gradient). It was assumed that the changed permeabilities would have little influence on flows moving northward through the reef complex from the Glass Mountains since this flow is controlled by the recharge assumed in the Glass Mountains (though a correlation between recharge and permeability may exist).

The flow through the reef complex at the Laguna submarine canyons during the geologic past was estimated to be 560 gpm based on the estimated transmissivity of 5,000 ft^2/day for the reef complex in this area (Hiss, 1975). For the sensitivity analysis, the transmissivity (and therefore, the permeability) of the reef complex in this region was assumed to range from 50 percent to 150 percent of this value. The resulting estimated flows through the reef complex at the Laguna submarine canyons ranged from 280 gpm to 840 gpm. Similar to the sensitivity analysis of the recharge to the reef complex in the Glass Mountains, the sensitivity analysis was performed by iteratively adjusting the heads at the boundaries representing the reef complex until the conceptualized and simulated inflows and outflow for the reef complex approximately balanced.

The influence of the conceptualized changes in the flow within the reef complex (resulting from changes in the permeability of the reef complex) are summarized in Figure G6 (Appendix G). The simulations suggest that increased flow through the reef complex at the Laguna submarine canyons would increase heads in the reef complex in southeastern Lea County. However, the simulations also suggest that heads in the reef complex in northern Pecos County would be increased by a similar magnitude because the increased permeabilities allow more flow to occur southward through the reef complex toward Pecos County. Because gradient in the reef complex between southeastern Lea and northern Pecos Counties remains similar, the simulated flow through the Fairway in Ward and Winkler Counties also remains similar.

8.2.6. Sensitivity Summary

Similar to sensitivity analysis of the calibration simulation, the sensitivity analysis of the simulation of the geologic past indicates that simulated flows through Ward and Winkler County are primarily controlled by the permeabilities of the Fairway in Ward and Winkler County and simulated hydraulic gradient through the Fairway in Ward and Winkler Counties. The gradient through the Fairway is largely controlled by the heads in the reef complex at the discharge boundaries in southeastern Lea and northern Pecos Counties and the model is sensitive to changes in parameters that influence these heads. Increased permeabilities or other changes to the model that result in increased gradients through the Fairway in Ward and Winkler Counties result in increased flows through the Fairway in Ward and Winkler Counties and an increased number of pore flushes during the geologic past.

9.0 SIGNIFICANT FINDINGS AND FUTURE RESEARCH

9.1 Significant Technical Findings

The multidisciplinary nature of the team making this study led to several technical breakthroughs. The one of most significance is the role of sulfate reducing microbes in altering the fluids and, possibly, the actual rock properties within the ROZ intervals. Sulfur water has been a long observed occurrence within the San Andres dolomites, as has the sour nature of the oils. The anaerobic bacteria must live in water, take their sulfur out of sulfur bearing chemicals (in our case, the interbedded, disseminated and nodular anhydrites) and will thrive if their food (hydrocarbons) is constantly available to them. The oil flushing mechanics in laterally flushing shelf carbonates could not be more ideal. Sections 4 and 7.2.5.3 outline the chemical reactions and the process in detail.

Another significant technical finding also relates to sulfur. The model for meteorically driven oil displacement is fundamental to this study. The recharge areas for the hydrological displacement may be obvious in retrospect but the caverns and karsted Guadalupian carbonates in New Mexico make for an obvious answer to the flushing fluid source. Although the study did not attempt in any detail to model the discharge areas, it became clear during the course of study that sulfur deposits are key indicators of water movement pathways. Sulfur maps of the Permian Basin were in vogue in the 1960-1970 decades and the maps and knowledge gained during the sulfur exploration phase of the Permian Basin assisted the team in reconstructing exit pathways. There are places in the Basin where sulfur occurs and has to be related to what are termed basement lineaments. Glasscock County has one, Irion County another and the discussed Pecos sulfur district a third. A hypothesis has developed regarding those free sulfur occurrences related to their presence associated with those lineament pathways wherein the sulfur rests up against the anhydrite cap atop the dolomites. Results of core examinations have also revealed free sulfur within vugs, at the base of the ROZs as well as in the commercial sulfur bodies, Those observations have led the team to conclude that the free sulfur occurrence requires a stagnant flow field. Future work will investigate this in more detail.

The landmark work of Hiss (1975) in his thesis suggested the critical nature of the Pecos River Valley incisement on the modern hydrology of the study area. Project studies confirmed this observation and assisted with calibration of the modern phase of the modeling. However, the hydrocarbon flushing phase clearly preceded the Pecos River incisement which offered less ability to calibrate the model for the important Tertiary flushing phase of ROZ development. It is here where the model is most vulnerable and led to long discussions about the paleo flow vectors in the San Andres in the Texas portion of the fairways. It is fair to say that much of that controversy remains and is related to the size and importance of the Hobbs area discharge mechanics of the model. This then controls whether the paleo flow conditions in Winkler, Ward and northern Pecos County are north or south. Some on the team believe the preponderance of data would suggest a southerly flow while the reported results herein indicate that those with the northern flow won out due to the pressure sinks around Hobbs. Such is the nature of research of our geologic past. What does remain as a conclusion for both camps is that the oil was indeed flushed and flushed to such an extent that the very little oil remained even in the top of porosity closures. One possible explanation is that there were two stages of paleo flow but that possibility would be difficult to prove with the information presently at hand.

Embedded within the two competing flow theories above is the hydraulic connectivity of the Capitan, Goat Seep (Grayburg) and San Andres reef complexes. While the west side of the Central Basin platform shelf was steeply plunging into the Delaware Basin to the west, the Delaware Basin was indeed shrinking making the three reef complexes prograde into the Delaware Basin as shown in Figures 7.4-7.7 (Appendix A-2). There are places in the Artesia fairway where the progradation was so slow that the three reefal zones are superimposed. The Vacuum field in Lea County, NM is one such area.

In spite of the gross simplification of the Texas Water Development Board mapping, considerable evidence exists that the Winkler and Ward County area has discrete hydrologic units for the Capitan, Goat Seep and San Andres. In fact, we would argue from the logs we have reviewed as a part of this project, that the San Andres has three differing reefal complexes instead of one with each separated hydraulically from the others. Figure 7.6 (Appendix A-2) adapted from Ward et al. 1986 , actually omits the Goat Seep and is ambiguous in this matter; we now believe that physical separation exists based upon the differing water chemistries and new logs drilled illustrating zonal isolation of the lower reefal rocks from the basinward Capitan. We also believe this issue to be a very important one due to the collision of two critical economic ventures: 1) possible (albeit very brackish) underground sources of drinking water and 2) possible commercial ROZ exploitation. Further work is justified

In addition to stacked reefal masses providing possible hydraulic connections, the presence of aforementioned lineaments can also provide fluid communication. As always in relatively poor permeability reservoirs, water salinity will provide the best evidence of connectivity.

Although very preliminary at this time, some evidence is mounting that there is a relationship between water salinity and residual oil saturation, i.e., high residual oil saturations requiring high water salinities. The theory revolves around the concept of low salinity waterflooding in oil (aka mixed) wet rocks wherein low salinity waters tend to produce incremental oil over what would be produced using waters of high salinity. With the emergent model for these zones below the oil/water contact being mother nature's waterfloods, the idea that mother nature could conduct low salinity waterfloods on paleo traps should also be valid. Should this relationship be proven true, the concern of protecting brackish water (USDWs) formations for possible human use from injection fluids during enhanced oil recovery operations may be unwarranted since levels of oil saturation are insufficient for economic oil recovery.

Three different sources of data have converged to suggest that the lateral displacement of oil from paleo traps is the proper explanation for the broad occurrence of ROZs in the San Andres formation of the Permian Basin. First, the tilted oil/water contacts observed and reported by

Brown (2001) can be evaluated to estimate the piezometric gradients by use of the formulae in Hubbert (1956). Secondly, the San Andres properties can be modeled using modern, first principle computer modeling tools with flow boundaries designed to replicate oil/water contact dipping surfaces (Koperna, 2006). Both approaches suggest flow gradients of 10-100 centimeters per year for oil/water contact dips of 10-100 feet per mile. Independently derived results from the subject study have provided a third confirmation of the range of flow gradients.

Finally, and perhaps most importantly, the concept of ROZ fairways and "greenfields," i.e., ROZs without main pay zones, has clearly gained some traction during the course of this project. Our project example, the Artesia (San Andres) Formation Fairway, is almost entirely a greenfield in Texas and, with some isolated but notable exceptions like the Vacuum and Hobbs fields, is very dominantly a greenfield in New Mexico. The significance of this new understanding cannot be overemphasized. The older transition zone model severely limited the areal distributions of the EOR targets to the main pay zones and directly beneath those existing fields. While large ROZs do, in fact, exist beneath existing fields such as the billion barrels of oil in place beneath the Seminole field (Biagoitti, 2008), greenfield ROZs of that size and larger can exist in regions devoid of primary production.

9.2 Future Research

Probably the single most important exercise to undertake in the Permian Basin is to acquire more regional data on the spatial distribution of San Andres ROZ fairways. Already many organizations are asking how large are the cumulative ROZ targets in the Basin. The size of the ROZ "prize" will have to be accomplished with public funds or left unanswered since industry interests are focused on project areas and do not align with regional studies of this sort. The magnitude of the oil resource and CO_2 sink for CO_2 capture in the Permian Basin are questions that both energy security proponents and environmentalists would seek. The results of this study are suggesting the enormity of the answer may lie in oil resources of the same magnitude as the total production to date but the ROZ team is very uncomfortable in making more precise estimates with such meager regional studies performed to date. As discussed earlier in the report, the ROZ Symposium, conducted very early in the project, touched the surface of the subject but the remainder of the work for this study was necessarily limited to developing and modeling a single case history of lateral sweep and, by way of limiting the effort, chose the San Andres portion of the Artesia fairway rimming the north and east sides of the Delaware Basin.

A large part of the ultimate answer of the magnitude of the Permian Basin ROZ resource will lie in the spatial approximation and volumetric calculations of the fairways but will also hinge on the estimation of the average value of residual oil saturations therein. Some surprises will inevitably come to light with, perhaps, average values lower than commercial cutoffs for economical EOR operations. Currently, the methodology for estimating residual oil saturations is site specific, expensive and devoid of a supporting science to regionally generalize local site data. The ROZ team has developed some hypotheses, based on water salinity, that require testing on a regional scale. Those hypotheses, even if proven of value in the Permian Basin, will then need to be applied and extended to other basins where conditions may be quite different and differing models will need to be visualized and tested.

One of the most significant findings to date has been in the understanding of the role of sulfur in the formation of a ROZ in the Permian Basin. The team believes that it has only begun to touch this surface of the importance of the sulfur chemicals. The sulfurous nature of the water, the sour oils and gases, and the black sulfur water are all signals that the microbial processes are at work and probably result in multivariate reactions and processes. Temperature, pressure, water salinity and time will all play a role in the formation of sulfur chemical and their progeny. Identification and modeling of those reactions could prove invaluable.

The transformation of anhydrite to calcite to dolomite via microbial and chemical transformation is another discovery of dramatic value. The team has, somewhat playfully, referred to this as reservoir alchemy wherein a dense, non-reservoir evaporitic material is transformed by nature into a porous reservoir rock. The significance of this cannot be overstated as the evidence is mounting that it leads to a better net pay to gross interval ratio and implies, perhaps, a better sweep efficiency for the ROZ interval than an otherwise comparable main pay zone.

The late stage formation of new dolomitic rock surfaces in the presence of oil would suggest an opportunity for a more oil wetting condition, perhaps explaining some of the observed high residual oil saturation values and greater targets for EOR. Attempting to simulate this process in the laboratory could prove enlightening.

And, finally, the microbial processes at work use oil as a driver for all the active biological and chemical processes. The current oil recovery projects in the ROZ would suggest this “footprint alteration” is not changing the oil properties in a major way but more research is needed to better understand which components in the oil are most affected. And does a “water washing” process further complicate the affected oils? Do either of the processes change miscibility or the proclivity for scale or asphaltene deposition?

What is clearly evident from the historic work of this project to date is that a whole new set of EOR targets has come to light. Heretofore, the oil and gas industry was inclined to believe that water floods are a small set of the group of primary oilfields and that EOR targets are an even more limited set of the waterflooded fields. What we understand now, at least in the Permian Basin, is that EOR targets can include mother nature’s waterfloods as well as those perfomed by humans. Natural processes have moved oil around, perhaps multiple times, in a significant percentage of the oil basins of the world. And, certainly in the Permian Basin, the volumetric extent of the natural waterfloods and hence, the EOR targets, is enormous and perhaps as large a target as the historical production to date.

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APPENDIX A-1

List of Technology Transfer Events for the Project

APPENDIX A-1

The following technology transfer events were conducted by project personnel and are available for viewing or downloading. All files are in PDF format unless otherwise indicated.

Carbon Capture and Storage Technology: Utilizing CO_2 EOR Industry Knowledge
July 14, 2011 – Texas Alliance Meeting, Corpus Christi
Robert D. Kiker

U.S. EOR Industry: An Overview – Current State of Play and Future Potential
July 12-13, 2011
L. Stephen Melzer

Carbon Capture and Storage Technology
April 20-21, 2011 – Southwest Petroleum Short Course
Robert D. Kiker

Emergence of Residual Oil Zones, Price, and CO2 Supply Factors
May, 2011 – CryoGas International Online Magazine (external website)
L. Stephen Melzer

The Excitement in Oil and Gas: Two Ongoing Revolutions
April, 2011 - CryoGas International Online Magazine (external website)
L. Stephen Melzer

The Concept of Hybrid Reservoirs: Deep Saline Formations + Residual Oil Zones as EOR and CCS Target Expansions
Presented May 10-11, 2011 to the USGS EOR- CO_2 Sequestration Workshop, Stanford University, L. Stephen Melzer

Residual Oil Zones (ROZs) and the Long Term Future of the Permian Basin (and Elsewhere)
Presented April 4, 2011 to the SPE Permian Basin Study Group of Gulf Coast Section
Dr. Bob Trentham, UTPB/CEED

Residual Oil Zones:Model, History, and Characteristics
Presented March, 2011 at Chevron's "Lunch and Learn" in Midland, Texas
Dr. Bob Trentham, UTPB/CEED

Residual Oil Zones: Oil Production and CO_2 Sequestration Target
Presented April, 2010 to the Sul Ross State University Geology Club
Dr. Bob Trentham, UTPB/CEED

Residual Oil Zones (ROZs) Moving From Science to Commercial Exploitation
Presented August, 2010 to AAPG GTW
Dr. Bob Trentham, UTPB/CEED

Residual Oil Zones (ROZs)and the long term future of the Permian Basin (and Elsewhere)
Presented to the Permian Basin Petroleum Association Annual Meeting (2010)
Dr. Bob Trentham, UTPB/CEED

Residual Oil ZonesFrom Science to Commercial Exploitation
Presented at the 4th Annual Wyoming EORI CO_2 Conference (2010)
Dr. Bob Trentham, UTPB/CEED

New Developments in Mature Fields and CO_2 Flooding
Presented April 21, 2011 to the Abilene Geological Society
L. Stephen Melzer

Residual Oil Zones – From Science to Commercial Exploitation
Presented June 14, 2010 to the Rocky Mountain Section – AAPG Conference
W. Hoxie Smith

Residual Oil Zones – From Science to Commercial Exploitation
Presented March 18, 2010 to the North Texas Geological Society, Wichita Falls, TX
Dr. Bob Trentham, UTPB/CEED

Residual Oil Zones – From Science to Commercial Exploitation
Presented March 17, 2010 to SIPES (Soc of Indep Prof Earth Scientists), Midland, TX
Dr. Bob Trentham, UTPB/CEED

Residual Oil Zones – From Science to Commercial Exploitation
Presented Feb 26, 2010 to scientists with ConocoPhillips
Dr. Bob Trentham, UTPB/CEED

From Science to Commercial Exploitation
Presented Feb 10, 2010 to the Roswell Geological Society, Roswell, NM
Dr. Bob Trentham, UTPB/CEED

From Science to Commercial Exploitation
Presented Feb 3, 2010 at the "Research Partnership to Secure Energy for America's Small Producer" Forum, Dr. Bob Trentham, UTPB/CEED

Phantom Discoveries and Completions Associated with Residual Oil Zones
Presented Dec 11, 2009 at the 2009 CO_2 Flooding Conference
Dr. Bob Trentham, UTPB/CEED

Phantom Discoveries and Completions Associated with Residual Oil Zones
Presented Nov 17, 2009 to the Permian Basin Soc for Sed Geology (SEPM)
Dr. Bob Trentham, UTPB/CEED

Notes from the October 22, 2009 Symposium – If you attended the Symposium, please feel free to supplement, clarify, or correct these notes, which were compiled from various sources. Please email info@residualoilzones.com with your updates.

Background Discussion
Steve Melzer, Melzer Consulting

Phantom Discoveries and Completions Associated with Residual Oil Zones
Dr. Bob Trentham, UTPB/CEED

Permian Basin Residual Oil Zones: From Conceptual Modeling of the Sweep Fairways to Data Acquisition to Hydrological Modeling, Presented Dec 11, 2011 at the 2011 CO_2 Flooding Conference http://www.co2conference.net/pdf/3.4-Trentham_Vance_-_ROZ_HydroGeological_Modeling-PermBasin_2011-CO2Flooding_Conf.pdf
Dr. Bob Trentham, UTPB/CEED, Mr. David Vance, ARCADIS, Steve Melzer, Melzer Consulting

APPENDIX A-2
Figures

Click here to view Appendix A-2 Figures (Note, Appendix A-2 will load as a separate PDF file and is 24 MB in size)

APPENDIX A-3

Water Databases Collected in the Project

Appendix A-3 Table 1
Inorganic Chemistry Data
Research Partnership to Secure Energy for America

EASTING	NORTHING	API NUMBER	UNIQUE ID	FIELD	SUR/TWP	BLK/RNG	SECTION	LEASE NAME	METHOD	SAMPLE DATE	UNITS	TDS	Ca	Mg	Na	K	Na+K	H_2CO_3	SO_4	Cl	CHARGE BALANCE	MASS BALANCE	pH
1543370.879	11077972.04	4250130071	42250102	WASSON				WASSON ODC UNIT #259			MG/L	2698	644	32	111	-3	-3	398	1300	213	-2.73E-03	0.92	7.9
1495265.672	11119126.77	4250110619	42003853	WASSON				MOORE #3	SEPARATOR	6/6/1952	MG/L	205116	3291	1106	75031	-3	-3	215	3313	122160	9.14E-04	0.99	7.2
1494066.878	11068172.34	4250110267	42000697	WASSON				WALKER #5	WELLHEAD	9/10/1951	MG/L	197062	7926	4807	61329	-3	-3	0	1550	121450	9.14E-04	0.99	8.6
1509146.879	11056896.89	4250110254	42003855	WASSON				MILLER A#8	SEPARATOR	5/1/1941	MG/L	200650	3942	1031	72542	-3	-3	186	3605	118691	2.41E-03	0.99	6.8
1512214.272	11056826.24	4250110252	42003858	WASSON				MILLER A-5	WELLHEAD	6/12/1951	MG/L	211636	2894	979	78170	-3	-3	424	3508	125661	9.18E-04	0.99	6.3
1542727.774	11048856.1	4250110244	42003861	WASSON				HAVENCAMP #4	WELLHEAD	6/13/1951	MG/L	67964	2131	572	22981	-3	-3	1046	3700	37534	7.48E-04	0.99	7.1
1549103.208	11059639.43	4250110211	42000552	WASSON				R.M. KENDRICK "A" 7		3/21/1956	MG/L	64470	2100	408	21646	306	-3	1068	4137	34903	5.23E-04	0.99	7.48
1478647.819	11064897.15	4250102948	42003867	WASSON				KNIGHT #1	SEPARATOR	8/3/1951	MG/L	250374	9432	5518	79460	-3	-3	272	2152	153540	9.18E-04	0.99	7.2
1515281.671	11056755.86	4250102680	42003869	WASSON				MILLER A-3	WELLHEAD	6/12/1951	MG/L	201465	2881	1208	73801	-3	-3	696	3335	119543	9.00E-04	0.99	7.2
1512297.931	11060465.61	4250101829	42001553	WASSON				ELLIOTT #3	SEPARATOR	5/29/1951	MG/L	221359	5463	2651	76682	-3	-3	494	2803	133267	9.15E-04	0.99	7.3
1524895.664	11074743.71	4250101822	42001034	WASSON				CHARLIE ANDERSON #1	BRADENHEAD	3/29/1952	MG/L	6132	153	56	2017	-3	-3	342	764	2800	-2.94E-03	0.97	8.3
1552487.983	11074130.54	4250101668	42003897	WASSON				N.W.WILLARD A#12	CASING HEAD	7/28/1950	MG/L	7642	122	82	2580	-3	-3	320	961	3539	-2.23E-04	0.97	7.5
1552408.575	11070490.95	4250101657	42001035	WASSON				WILLARD "C" #4	BRADE HEAD CONNECTION	1/20/1954	MG/L	84106	3892	1765	25827	-3	-3	375	2337	49910	8.25E-04	0.99	5.5
1473481.575	11105078.98	4250101559	42003677	WILDCAT				F.D. SUDDUTH #1	WELLHEAD	2/4/1955	MG/L	221217	6900	3487	73901	-3	-3	262	1667	135000	6.69E-04	0.99	7
1501219.32	11111703.67	4250101507	42003909	WASSON				KELLER #4	SEPARATOR	8/16/1949	MG/L	216496	4964	440	78578	-3	-3	1110	3182	128223	9.08E-04	0.99	6.7
1515198.34	11053116.51	4250101107	42003873	WASSON				L. DOWELL #1	WELLHEAD WHILE SWABBING WELL.	6/12/1952	MG/L	166809	5695	1009	57460	-3	-3	400	3312	98933	8.82E-04	0.99	7.4
1527715.378	11063755.99	4250100371	42003877	WASSON				WILLARD A-7	SEPARATOR	5/28/1951	MG/L	214542	3698	1425	77716	-3	-3	689	3418	127596	9.17E-04	0.99	7.3
1469271.359	11057840.41	4250100246	42003878	WASSON				RANDALL #1	SEPARATOR	5/30/1951	MG/L	204849	7226	4465	65579	-3	-3	214	2215	125151	9.18E-04	0.99	7.2
1524648.608	11063825.24	4250100223	42003879	WASSON				N.W. WILLARD D-4	WELLHEAD	6/13/1951	MG/L	79263	2204	892	26881	-3	-3	977	3553	44756	8.04E-04	0.99	7.1
1533848.937	11063618.3	4250100215	42003882	WASSON				WILLARD A #10	SEPARATOR	5/28/1951	MG/L	216020	3659	1422	78352	-3	-3	711	3309	128568	9.12E-04	0.99	7.3
1549342.41	11070557.99	4250100202	42003678	WASSON				C. WEBBER B #3	BRADENHEAD	1/31/1954	MG/L	8445	172	133	2827	-3	-3	163	670	4480	-1.70E-03	0.98	8.2
1509566.816	11075094.01	4250100160	42003885	WASSON				MORRIS #2	WELLHEAD	5/28/1951	MG/L	237514	8626	6259	74167	-3	-3	256	1889	146317	9.21E-04	0.99	6.9
1452384.884	10617812.67	4249505387	42905554	EMPEROR				SM HALLEY B 15			MG/L	147803	11400	424	-3	-3	44830	433	1706	89010	8.65E-04	0.99	
1482683.792	10584337.38	4249502502	42905331					SEALY-SMITH FDN 1	DST		MG/L	238626	2198	1002	-3	-3	89530	447	4649	140800	2.15E-03	0.99	
1489983.646	10496842.63	4247504419	42904989	WARD SOUTH				DB DURGIN 72			MG/L	53878	189	835	-3	-3	17830	9686	2788	22550	1.03E-03	0.9	
1519860.517	10437949.48	4247503036	42904860	PECOS VALLEY				FM WHITE 4			MG/L	5280	766	237	-3	-3	641	391	2410	1030	-1.26E-03	0.99	
1473791.615	10471754.51	4247500238	42003944	WARD SOUTH				MILLER #3	WELL HEAD	6/13/1949	MG/L	6003	754	166	885	-3	-3	964	1777	1313	-1.22E-03	0.89	7.4
1691556.236	11133281.87	4244500551	42000444					SHELL OIL-FLOYD #1		6/3/1957	MG/L	213830	4016	1885	76337	-1	-3	779	2878	127842	4.58E-04	0.99	6.36
2063854.704	10964883.46	4241501205	42003033					T.W. POLLARD NO. 1	WELLHEAD VALVE	11/12/1956	PPM	65681	2036	1107	21390	-3	-3	524	4244	36380	6.75E-04	0.99	
1863108.818	10406509.22	4238311365	42000140	JOHN SCOTT				J. R. SCOTT #2	WELLHEAD	6/23/1954	MG/L	30355	2749	1646	6250	-3	-3	129	1341	18240	5.17E-04	0.99	6.45
1978402.041	10365253.21	4238300236	42105334				14	UNIT #1		10/4/1955	PPM	18123	680	486	-3	-3	5426	252	1680	9600	4.67E-04	0.99	7.18
1585296.622	10429272.21	4237107522	42904458	ABELL NORTH				RG PIPER A 2	PRODUCTION AND DEVELOPMENT TEST		MG/L	6778	404	122	-3	-3	1707	1111	1414	2020	-1.42E-03	0.91	
1543035.273	10353765.64	4237107038	42904452					MACEY B 1			MG/L	5912	782	256	-3	-3	780	227	2541	1326	-9.78E-04	0.97	
1646728.587	10336481.84	4237104729	42904366	WENTZ				MAUDE B WANGERIN 1	DST		MG/L	123241	2320	571	-3	-3	44570	432	4468	70880	0	1	
1649141.117	10333443.15	4237104729	42904366	WENTZ				MAUDE B WANGERIN 1	DST		MG/L	123241	2320	571	-3	-3	44570	432	4468	70880	1.26E-03	0.99	
1563583.539	10436999.47	4237104528	42904345	DAMERON				SIDLO 2	SWAB		MG/L	76618	13250	2904	-3	-3	10810	194	1760	47700	-4.76E-03	0.99	
1556718.316	10408040.96	4237103824	42904303					WT SHEARER-HUMBLE 1			MG/L	5198	729	235	-3	-3	585	267	2452	911	-9.49E-04	0.96	
1600478.95	10407137.36	4237103188	42904270					HJ EATON 1			MG/L	5604	751	196	543	54	-3	329	2743	988	-0.07	0.96	
1534918.098	10412149.7	4237102748	42904180	PECOS VALLEY				HJ EATON A 1			MG/L	5342	759	205	-3	-3	683	450	1898	1348	-3.72E-03	0.95	
1525542.078	10412356.37	4237101772	42904166	PECOS VALLEY				REDMOND B 1			MG/L	5233	723	253	-3	-3	556	356	2402	921	-5.73E-03	0.96	
1643924.973	10366097.67	4237101270	42105352	WENTZ				HART #1	DST	30-Mar-53	MG/L	48156	1842	1325	-3	-3	14335	691	4347	25616	0	0.99	7.0
1524735.648	10375994.14	4237100997	42904132					RG HEINER ETAL 1			MG/L	5109	733	237	-3	-3	565	50	2573	931	-1.16E-03	0.98	
1500123.343	10394738.95	4237100598	42904129					EE BONEBRAKE 1	WELLHEAD OR WELL BLEEDER		MG/L	35903	556	369	12420	154	-3	421	2773	19200	-2.59E-03	0.99	
1550544.92	10411810.86	4237100587	42904127	LEHN-APCO NORTH				MD SELF 1			MG/L	82131	883	1913	-3	-3	26900	525	13660	38250	4.49E-04	0.99	
1591322.914	10418235.59	4237100086	42904106	ABELL				OW WILLIAMS 1			MG/L	15187	975	223	-3	-3	4094	1361	2438	6096	2.71E-04	0.95	
1556585.649	10425015.01	4237100034	42904081	ABELL EAST				STATE-CORRIGAN A 2	DST		MG/L	59312	2982	2588	-3	-3	15760	707	3195	34080	0	0.99	
1557027.817	10422586.32	4237100034	42904081	ABELL EAST				STATE-CORRIGAN A 2	DST		MG/L	59312	2982	2588	-3	-3	15760	707	3195	34080	4.44E-03	0.99	
1547497.899	10415514.38	4237100006	42904071					SLOAN BLAIR 1			MG/L	5407	764	339	-3	-3	461	396	2402	1045	-5.32E-04	0.96	
1737771.718	10582914.94	4232901568	42000433	SWEETIE PECK				JUNE TIPPETT #19		3/28/1956	MG/L	208780	16496	3854	57598	414	-3	373	1116	128552	9.18E-04	0.99	8.57
2060117.879	10415523.2	4223500440	42000504	KETCHUM MOUNTAIN				J.R. SCOTT #5		8/2/1957	MG/L	55169	1707	708	18066	-1	-3	173	6275	28144	1.67E-03	0.99	7.93
1984790.446	10725331.41	4222703908	42002350					23		1/31/1955	MG/L	69398	2508	841	22859	-3	-3	634	3058	39554	2.51E-04	0.99	
1987887.643	10725303.52	4222703886	42002355	HOWARD-GLASSCOCK						1/31/1955	MG/L	87377	2818	994	29407	-3	-3	798	2002	51340	3.04E-04	0.99	
1947624.285	10725687.8	4222703520	42002636	HOWARD-GLASSCOCK				HART PHILLIPS #29	AT WELLHEAD	6/13/1957	MG/L	82067	2879	1095	27140	-3	-3	853	1758	48342	7.96E-04	0.99	5.91
1950721.45	10725656.57	4222703515	42251003	HOWARD-GLASSCOCK				H PHILLIPS #22		3/3/1951	MG/L	86166	3795	1630	26948	-3	-3	1026	1303	51463	7.91E-04	0.99	6.5
2035370.554	10859544.54	4222703499	42000013	CORONET				C. L. JONES "A" #1	DRAIN OFF TANK BOTTOM AND TREATED W/VISCO	4/22/1953	MG/L	105059	9206	3470	25659	-3	-3	589	1891	64244	7.01E-04	0.99	7.19
1657301.047	11265026.42	4221910071	42250336	LEVELLAND				LEVELLAND UNIT #370	WELLHEAD		MG/L	95631	10500	1760	23241	-3	-3	400	1530	58200	6.22E-04	0.99	6.8
1663738.365	11283119.97	4221902489	42250227	LEVELLAND				LEVELLAND UNIT #71	WELLHEAD		MG/L	257339	27900	5220	62724	-3	-3	165	330	161000	6.98E-04	0.99	6.5
1666785.421	11283063.22	4221901838	42250680	LEVELLAND				LEVELLAND UNIT 70	WELLHEAD		MG/L	263656	34300	6200	56735	-3	-3	171	250	166000	6.91E-04	0.99	6.4
1660691.314	11283177	4221901830	42250679	LEVELLAND				LEVELLAND UNIT #73	WELLHEAD		MG/L	255512	27400	5470	62168	-3	-3	154	320	160000	7.01E-04	0.99	6.6
1947587.437	10722049.7	4217300969	42000138	HOWARD-GLASSCOCK				HART PHILLIPS #30	WELLHEAD	2/4/1954	MG/L	77236	2792	1042	25374	-3	-3	942	1976	45111	6.44E-04	0.99	6.61
1950684.929	10722018.47	4217300955	42001367	HOWARD-GLASSCOCK				H. PHILLIPS #3		5/23/1949	MG/L	67436	2279	761	22369	-3	-3	1127	3108	37792	7.71E-04	0.99	6.58
1947550.589	10718411.63	4217300954	42001359	HOWARD-GLASSCOCK				HART PHILLIPS #2	WELLHEAD	2/4/1954	MG/L	66373	2226	940	21882	-3	-3	1332	1283	38710	6.44E-04	0.98	6.85

RPSEA
ARCADIS

Appendix A-3 Table 1
Inorganic Chemistry Data
Research Partnership to Secure Energy for America

EASTING	NORTHING	API NUMBER	UNIQUE ID	FIELD	SUR/TWP	BLK/RNG	SECTION	LEASE NAME	METHOD	SAMPLE DATE	UNITS	TDS	Ca	Mg	Na	K	Na+K	H_2CO_3	SO_4	Cl	CHARGE BALANCE	MASS BALANCE	pH
1944452.772	10718443.14	4217300052	42105312	HOWARD-GLASSCOCK	S 2		22	COFFEE #5		5/8/1953	MG/L	66133	1684	1015	-3	-3	22218	1454	1748	38013	1.40E-03	0.98	6.7
1954886.336	11140544.37	4216901769	42000306	HUNTLEY				C.N. BROWN #1		1/23/1955	MG/L	247425	2757	3909	87324	1047	-3	401	1449	150738	3.56E-04	0.99	6.81
1522260.683	10958292.61	4216503307	42001612	CEDAR LAKE				M L DOSS #1	DST #1	5/17/1951	MG/L	296524	2698	508	112124	158	-3	112	5614	175255	3.95E-04	0.99	7.3
1513698.488	10987612.75	4216503270	42003579	ALSABROOK				#1 FRED GLANTON	DST	11/1/1955	MG/L	12763	910	136	3488	-3	-3	461	2588	5280	-4.84E-03	0.98	
1548066.728	11012328.53	4216502871	42003503	WILDCAT				W.S. WIMBERLEY NO. 1	DRILL STEM TEST	8/1/1955	MG/L	20149	630	245	5788	-3	-3	502	10104	3000	4.80E-05	0.99	7.7
1530046.909	11030932.97	4216502330	42105363	WASSON			38	COX #1		2/22/1944	PPM	69403	4080	1920	-3	-3	19363	1220	3220	39600	5.97E-04	0.99	
1582801.728	10909653.14	4216502136	42003517	ROBERTSON				#1 LANDRATH A	SWBG. OPEN HOLE	11/1/1956	MG/L	44600	1420	601	14900	-3	-3	724	214	26700	4.30E-05	0.99	8.5
1557438.433	11019406.26	4216502098	42003513	O D C				R.V. CHARHOLTZER #1	DST	10/1/1957	MG/L	4530	728	6	768	-3	-3	36	1790	1200	-0.01	0.99	7.2
1704715.255	11009255.94	4216501556	42105371	CEDAR LAKE			10	J. & W. #4		4/3/1951	MG/L	70134	2184	892	-3	-3	23310	761	3927	39060	8.29E-04	0.99	7.9
1617771.822	10963545.5	4216501149	42105378	HOMANN				CUNNINGHAM #1		5/27/1945	PPM	37650	1585	548	-3	-3	11865	636	3720	19200	9.09E-03	0.98	
1585227.115	11026098.01	4216500596	42003574	WILDCAT				F.A. FOX #1	DST	7/1/1956	MG/L	97042	2210	830	34118	-3	-3	355	4809	55320	-3.76E-04	1	7.3
1527223.246	11041919.75	4216500526	42001697					A.L. WASSON "51" NO. 8	WELLHEAD BLEEDER LINE	12/16/1957	MG/L	81000	2500	2400	22200	470	-3	963	3100	41100	0.02	0.89	6.85
1588662.472	10894971.46	4216500381	42105386	MEANS NORTH			19	#1-19 MAYO	DST		MG/L	199054	2295	2078	-3	-3	72000	506	3825	118350	-4.80E-04	0.99	6.3
1462484.857	10905089.79	4216500253	42000458					SPRAGUE #1	DST #1	7/3/1954	PPM	212596	4480	2333	75172	953	-3	268	1724	130127	6.94E-04	1.01	6.82
1568637.464	10968196.09	4216500042	42003588	SEMINOLE				T.S. RILEY B 8	WELLHEAD	3/15/1955	MG/L	35478	1770	472	10664	-3	-3	1684	3188	17700	-1.35E-03	0.97	7.1
1565950.889	10986456.26	4216500026	42003500	SEMINOLE				RILEY "C" #2	SEPARATOR	8/28/1957	MG/L	49400	1750	461	16200	-3	-3	1230	3670	26100	-1.09E-03	0.98	7.2
1692879.06	11034947.63	4216500017	42000654	ADAIR				LILES #1	WELLHEAD	2/3/1950	MG/L	61817	2515	852	19774	-3	-3	746	3593	34336	7.62E-04	0.99	7.5
1703454.533	10936472.08	4216500001	42000695					BURLESON #1	DST #2	3/5/1952	MG/L	55415	1756	649	18384	-3	-3	824	3573	30229	7.27E-04	0.99	7.6
1611131.75	10628853.91	4213508454	42003525	HARPER				COWDEN NO. 3	HEATER TREATER	6/27/1955	MG/L	53167	790	2128	16348	-3	-3	233	3428	30240	-7.06E-04	0.99	5.9
1540973.179	10688538.32	4213508308	42000891	T X L				WILLIAMSON #4	WELL HEAD	5/16/1956	MG/L	28963	1060	188	9460	-3	-3	136	4079	14040	-2.99E-03	0.99	
1609910.602	10723485.86	4213507759	42003531	COWDEN NORTH				BLAKENEY A #5	WELLHEAD	7/29/1956	MG/L	24854	190	1816	6374	-3	-3	546	2738	13504	-0.01	1	8.2
1547490.319	10702952.06	4213505493	42003824	GOLDSMITH				RUMSEY D-1	TANK	5/19/1951	MG/L	187414	11468	5391	52545	-3	-3	561	2878	114572	8.74E-04	0.99	7
1550510.826	10699247.57	4213505488	42003541	GOLDSMITH				RUMSEY C #9	TEST SEPARATOR	10/18/1955	MG/L	121678	3210	1416	41661	-3	-3	533	3858	71000	7.83E-05	0.99	8.2
1550589.53	10702884.86	4213505487	42003821	GOLDSMITH				RUMSEY C #8	TUBING	10/3/1951	MG/L	380384	2939	8713	132484	-3	-3	452	4578	231219	9.63E-04	0.99	6.7
1568877.953	10687938.28	4213505474	42004283	GOLDSMITH				DAVID RUMSEY A #12	WELLHEAD	12/7/1956	MG/L	109300	2600	668	38600	-3	-3	570	3880	63000	-1.59E-04	0.99	7.8
1586808.405	10654815.62	4213505438	42000981	T X L				TXL "O" #1	DST #1	5/19/1950	MG/L	212225	3048	965	78018	-3	-3	637	5472	124086	9.01E-04	0.99	7.1
1606938.639	10574360.59	4213505023	42003953	JORDAN				B#8-A	WELL HEAD	9/29/1950	MG/L	98894	2420	518	34804	-3	-3	1020	4857	55275	8.26E-04	0.99	
1657384.123	10609775.17	4213504807	42002418	COWDEN SOUTH				4		10/30/1948	MG/L	98752	2553	384	34810	-3	-3	1401	3919	55663	3.00E-04	0.99	
1606449.146	10705360.32	4213504388	42003958					B. M. BLAKENEY B#5	TEST SEPARATOR	11/5/1953	MG/L	58674	1768	736	19333	-3	-3	1332	1566	30939	0.03	0.93	7.3
1612574.974	10701599.36	4213504383	42000908	COWDEN NORTH				BLAKENEY B NO. 3	TEST SEPARATOR (AFTER BLEEDING OFF)	6/14/1955	MG/L	53345	2650	752	16555	-3	-3	326	5082	30000	-0.02	1.03	
1615817.982	10708812.93	4213504382	42003533	COWDEN NORTH				BLAKENEY A #7	SEPARATOR	2/9/1955	MG/L	65155	3050	996	20077	-3	-3	396	2656	37680	-6.99E-03	0.99	7.4
1646119.394	10671840.34	4213503825	42000453					J.L. JOHNSON #1		7/5/1957	MG/L	92500	5548	3682	24060	212	-3	123	2900	55614	9.68E-04	0.99	6.15
1660424.784	10606080.71	4213503518	42002423	COWDEN SOUTH				3		2/25/1949	MG/L	229459	2436	1806	84219	-3	-3	521	4463	135966	4.23E-04	0.99	
1566393.952	10717102.51	4213503507	42002444	ANDECTOR				3		2/9/1948	MG/L	8107	689	94	1851	-3	-3	998	2699	1778	-8.79E-04	0.93	
1557334.328	10728212.9	4213503472	42002436	ANDECTOR				2		8/31/1947	MG/L	13705	1110	66	3783	-3	-3	202	2511	6029	-4.87E-04	0.99	
1569031.435	10695212.86	4213502635	42001526	GOLDSMITH				COWDEN #7	TEST SEPARATOR	6/7/1950	MG/L	393032	841	12871	132325	-3	-3	308	14657	232031	9.40E-04	0.99	6.1
1614381.284	10636066.71	4213502623	42105240	HARPER	S 2		13	COWDEN WRIGHT #3	WELL	2/23/1956	MG/L	124514	3369	2650	38709	-3	-3	1215	5130	73440	-0.02	0.99	7.6
1543835.618	10677558.95	4213502436	42002447	T X L				3 ALMA		3/1/1947	MG/L	147236	2742	24	53823	-3	-3	-3	5810	83459	1.78E-03	0.99	
1572054.927	10691510.29	4213502264	42003887	GOLDSMITH				COWDEN #3	WELL HEAD	9/27/1950	MG/L	207395	3383	8331	64286	-3	-3	423	6829	124144	7.59E-04	0.99	7.2
1883483.234	10278955.92	4210503014	42000015	SHANNON				SHANNON ESTATE "B" #17	AT WELL	10/28/1954	MG/L	83210	2309	1254	27705	-3	-3	787	4328	46827	5.96E-04	0.99	7.92
1880432.659	10286266.57	4210502991	42255425	SHANNON			23	SHANNON B-4	PRODUCED ALONG WITH THE OIL	12/4/1944	MG/L	42378	806	336	14703	-3	-3	2411	1673	22450	5.03E-04	0.97	
1999535.291	10274138.14	4210502620	42000283					MELHE HOLT #2		5/24/1953	MG/L	74098	2104	971	24686	200	-3	501	4110	41497	5.39E-04	0.99	7.3
1656039.125	10537035.04	4210305478	42105255				8	ADAM #1	SWAB FLOW	10/1/1957	MG/L	67457	2184	714	-3	-3	22580	1029	3150	37800	1.24E-03	0.99	6.3
1603609.452	10563512.09	4210305307	42000290	JORDAN				UNIVERSITY 23 #7		9/9/1957	MG/L	98874	2902	934	33684	-1	-3	575	5086	55614	1.59E-03	0.99	7.53
1616127.966	10566902.04	4210303087	42003452					V. TEX A #5	WELLHEAD	1/21/1956	MG/L	40458	1460	56	12812	-3	-3	2011	2731	20880	-0.03	0.96	7.1
1636523.988	10493744.27	4210303072	42000850	MCELROY				UNIV. "D" #1	WELL HEAD	4/21/1954	MG/L	150198	16934	10040	24603	-3	-3	2721	1221	94879	-1.69E-04	0.99	6.2
1636454.782	10490107.56	4210303071	42001645	DUNE SE				UNIV. E #2		6/12/1957	MG/L	51246	1785	757	16172	-1	-3	1991	5112	25395	2.76E-04	0.97	6.75
1593757.741	10538242.66	4210302987	42000792	C-BAR				CONNELL #5	WELLHEAD	3/19/1954	MG/L	86785	2852	1195	28629	-3	-3	975	3933	49201	8.15E-04	0.99	7.5
1599985.78	10538116.86	4210302986	42000957	C-BAR				CONNELL #4	TEST SEPARATOR	9/13/1950	MG/L	104299	7345	4439	25852	-3	-3	360	2725	63577	8.26E-04	0.99	7.6
1596871.758	10538179.62	4210302984	42000962	C-BAR				CONNELL #2	TEST SEPARATOR	9/13/1950	MG/L	110992	5712	3497	31733	-3	-3	500	2331	67218	8.49E-04	0.99	7.6
1593979.1	10549152.97	4210302982	42001828	C-BAR				W.K. CONNELL B #1	STOCK TANK	12/29/1955	MG/L	72193	2400	1265	23167	-3	-3	1486	3675	40200	-6.13E-04	0.98	8.1
1605199.166	10487078.37	4210302978	42003482	LEA				BARNSLEY C-5	WELLHEAD-SWABBING	8/30/1955	MG/L	97114	3290	2202	30777	-3	-3	198	3647	57000	-1.08E-04	0.99	6
1592503.408	10476419.47	4210302973	42000883	SAND HILLS				BARNSLEY B-1	(12% WATER PRODUCTION)	8/31/1955	MG/L	102506	1880	721	36377	-3	-3	924	5604	57000	-4.60E-04	0.99	8
1586264.277	10476546.62	4210302965	42003490	LEA				BARNSLEY C #6	WELLHEAD-SWABBING	5/31/1956	MG/L	134131	2030	743	48641	-3	-3	534	5983	76200	-2.13E-04	0.99	7.8
1655702.89	10518850.78	4210302930	42000651	DUNE				#1 UNIVERSITY 17	WELLHEAD	9/15/1954	MG/L	20872	90	868	6490	-3	-3	483	1848	11800	-0.02	1.02	7.8
1522749.258	11249614.79	4207900206	42003373	LEVELLAND				MARTIN B #1	WELLHEAD	1/24/1956	MG/L	211571	15600	5047	50362	-3	-3	465	125	132000	-0.04	0.96	5.5
1574058.931	11222984.68	4207900204	42001054	SLAUGHTER				C.S. DEAN #9	WELL HEAD	4/1/1949	MG/L	263917	14804	5784	77351	-3	-3	359	1173	163289	-5.37E-03	0.99	6.2
1573981.459	11219343.79	4207900203	42000685	SLAUGHTER				C.S. DEAN #8	WELLHEAD	8/25/1951	MG/L	225474	10516	2021	73976	-3	-3	293	1083	137585	9.00E-04	0.99	6.8
1571084.274	11226690.68	4207900200	42000794	SLAUGHTER				C. S. DEAN #5	WELLHEAD	3/31/1949	MG/L	280550	15767	4769	85702	-3	-3	300	959	173053	9.04E-04	0.99	6.7
1574136.404	11226625.6	4207900198	42005130	RHODES				C. S. DEAN #3	WELLHEAD	8/26/1951	MG/L	267079	12695	6024	81812	-3	-3	216	1135	165197	9.17E-04	0.99	7.3
1558717.599	11219672.01	4207900196	42001056	RHODES				C.S. DEAN #1	SEPARATOR	3/23/1949	MG/L	266119	10554	3268	87910	-3	-3	767	1232	162387	9.09E-04	0.99	6.5
1633277.279	10810367.74	4200300997	42003392	WEMAC				T.F. TEAGUE #1	DST	4/1/1957	MG/L	21200	350	95	7460	-3	-3	248	2690	10300	-7.73E-04	0.99	7.6

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RPSEA ARCADIS

EASTING	NORTHING	API NUMBER	UNIQUE ID	FIELD	SUR/TWP	BLK/RNG	SECTION	LEASE NAME	METHOD	SAMPLE DATE	UNITS	TDS	Ca	Mg	Na	K	Na+K	H_2CO_3	SO_4	Cl	CHARGE BALANCE	MASS BALANCE	pH
1644946.496	10773751.89	4200300598	42003395	FASKEN				UNIVERSITY "A" #1		4/17/1956	MG/L	222856	3500	1944	80282	-3	-3	202	4928	132300	-6.18E-04	1	8.2
1548675.827	10757513.4	4200300448	42003404	MARTIN				UNIV. 11 #2	WELL HEAD	7/18/1955	MG/L	90422	2668	758	30874	-3	-3	1066	3936	51120	-2.10E-04	0.99	7.1
1551691.423	10753808.75	4200300434	42000811	MARTIN				UNIV. 11 (SEC. 13) "B"-1	WELLHEAD	7/22/1955	MG/L	47441	1120	1280	15153	-3	-3	599	1929	27360	-1.71E-04	0.99	7.8
1593262.502	10818442.3	4200300400	42003744	SHAFTER LAKE				SHEPARD-STATE #1	SEPARATOR	6/11/1954	MG/L	110296	5427	2805	32695	-3	-3	1236	2532	65601	8.57E-04	0.99	7.3
1548754.864	10761150.96	4200300373	42000813	MARTIN				UNIV. 11 (SEV 12) 2-A	SEPARATOR	12/6/1949	MG/L	107858	2052	4184	33085	-3	-3	1765	3539	63233	6.38E-04	0.99	7.5
1548517.754	10750238.32	4200300327	42003799	MARTIN				UNIT. 11 SEC. 23 #1	TANK	12/8/1949	MG/L	94608	3626	2114	29610	-3	-3	373	3348	55547	8.12E-04	0.99	6.9
1551848.842	10761083.88	4200300312	42003436	MARTIN				UNIV. 11 B #4	WELLHEAD	5/16/1956	MG/L	73672	1980	894	24797	-3	-3	889	4432	40680	-6.30E-04	0.99	7.6
1286832.258	11219382.09	3002521045	30903987	LEA	S 10	E 32	26	STATE E 2			MG/L	247026	3400	1370	-3	-3	90900	356	3000	148000	5.59E-05	0.99	
1303375.499	11262614.89	3002521038	30903984	FLYING M	S 9	E 33	17	STATE FMB 3	SWAB		MG/L	263094	3007	1579	-3	-3	98100	457	3251	156700	6.58E-03	0.99	
1283779.479	11219473	3002521029	30903983	MESCALERO	S 10	E 32	27	N M STATE AF TB-2 3	SWAB		MG/L	255171	4200	1940	-3	-3	92400	351	2280	154000	-1.54E-04	0.99	
1326013.952	10985143.15	3002520954	30903963	VACUUM	S 18	E 35	6	STATE OF NM AB 7			MG/L	168780	5280	1940	-3	-3	57200	360	3000	101000	-2.43E-04	0.99	
1426622.527	10949668.12	3002520933	30903946	HOBBS	S 19	E 38	5	HD MCKINLEY 5			MG/L	45625	2359	319	14746	-3	-3	-3	1251	26950	1.80E-04	0.99	
1309473.309	11262436.87	3002520807	30903894	FLYING M	S 9	E 33	16	STATE A 1	WELLHEAD OR WELL BLEEDER		MG/L	237663	1900	630	-3	-3	90700	633	2800	141000	6.49E-03	0.99	
1406183.18	11226972.01	3002520735	30903874	CROSSROADS SOUTH	S 10	E 36	16	CROSSROADS DEVONIN UNT 1	DST		MG/L	11788	1177	74	-3	-3	2923	631	2111	4872	6.53E-04	0.97	
1284105.162	11230393.18	3002520731	30903870	MESCALERO	S 10	E 32	15	WHITE-STATE 1	DST		MG/L	297896	2209	713	-3	-3	112800	544	8930	172700	1.73E-03	0.99	
1312416.6	11258707.79	3002520644	30903833		S 9	E 33	21	SOUTHERN MINERALS-ST 3			MG/L	352358	40010	27910	-3	-3	37660	658	420	245700	-0.07	0.99	
1303268.892	11258974.44	3002520641	30903831	FLYING M	S 9	E 33	20	SKELLY-STATE 5	WELLHEAD OR WELL BLEEDER		MG/L	228200	1798	1334	-3	-3	86070	597	1601	136800	6.13E-03	0.99	
1306318.12	11258885.28	3002520640	30903830	FLYING M	S 9	E 33	20	SKELLY-STATE 3	WELLHEAD OR WELL BLEEDER		MG/L	228048	2000	486	-3	-3	87040	642	1480	136400	5.58E-03	0.99	
1287265.195	11233942.44	3002520626	30903828	MESCALERO	S 10	E 32	14	STATE BL 2			MG/L	287275	4600	510	-3	-3	107000	165	3000	172000	1.75E-03	0.99	
1430436.736	10978697.82	3002520524	30903810	BISHOP CANYON	S 18	E 38	9	HUSTON 2			MG/L	60250	12020	6836	-3	-3	0	1625	949	38820	9.68E-03	0.98	
1276264.42	11274350.86	3002520380	30903752	BAR-U	S 9	E 32	5	STATE 5 1	DST		MG/L	87460	3909	521	-3	-3	28990	1203	3437	49400	5.50E-03	0.99	
1312627.852	11265988.79	3002520248	30903703	FLYING M	S 9	E 33	9	SHELL-STATE 1	WELLHEAD OR WELL BLEEDER		MG/L	246810	2796	1334	-3	-3	92430	252	1498	148500	6.23E-03	0.99	
1317000.973	10992682.73	3002520228	30903698	VACUUM	S 17	E 34	35	STATE H-35 9	DST		MG/L	226456	2405	2075	-3	-3	83220	668	4788	133300	5.96E-03	0.99	
1323250.913	10996145.51	3002520212	30903693	VACUUM	S 17	E 34	25	SWIGART 2			MG/L	199907	2217	823	-3	-3	74640	759	3868	117600	3.00E-03	0.99	
1373529.836	10921932.61	3002520193	30903686	MONUMENT	S 20	E 36	2	STATE A 2	SWAB		MG/L	11847	1015	519	-3	-3	2467	1756	0	6090	4.38E-04	0.92	
1430344.587	10975059.26	3002520169	30903681	BISHOP CANYON	S 18	E 38	9	HUSTON 3	SWAB		MG/L	24317	2171	1020	-3	-3	5048	1812	2806	11460	9.31E-04	0.96	
1367304.33	11257159.71	3002520048	30903648	JENKINS	S 9	E 35	20	BARNES 1	PUMPING		MG/L	227350	6880	1780	-3	-3	78720	1470	2500	136000	1.03E-03	0.99	
1436036.628	10956711.58	3002512509	30903623	HOBBS	S 18	E 38	34	TURNER 2			MG/L	26230	498	671	-3	-3	8400	1841	890	13930	4.84E-03	0.96	
1382865.482	10925322.99	3002512476	30903614	MONUMENT	S 19	E 36	36	GRAHAM-STATE F 3			MG/L	26344	3454	1192	-3	-3	4687	611	-3	16400	2.42E-03	0.98	
1448274.08	10828995.87	3002512182	30903567	DRINKARD	S 22	E 38	32	TR ANDREWS 1			MG/L	132703	3603	1402	-3	-3	45770	707	1511	79710	-3.75E-04	0.99	
1415719.822	10764298.8	3002511310	30903351	LANGLIE-MATTIX	S 24	E 37	32	STATE A 2	SWAB		MG/L	18957	855	590	-3	-3	5131	2312	1095	8974	1.27E-03	0.93	
1412626.133	10764378.12	3002511308	30903347	LANGLIE-MATTIX	S 24	E 37	32	STATE A 1	SWAB		MG/L	25094	1016	503	-3	-3	7112	1788	965	13710	-0.04	0.96	
1433109.356	11084227.5	3002509866	30903197	DENTON	S 15	E 37	1	PRIEST 5			MG/L	210507	4480	2620	-3	-3	75700	207	4500	123000	0.02	0.99	
1319107.464	10850630.39	3002508473	30902962		S 22	E 34	7	SLATTERY PERMIT 1			MG/L	4460	277	147	-3	-3	1061	158	243	2502	-0.04	0.96	
1234480.9	11009713.46	3002508026	30902883	MALJAMAR	S 17	E 32	18	MITCHELL B 40			MG/L	205760	1490	830	-3	-3	77400	390	5650	120000	8.87E-04	0.99	
1234367.813	11006075.31	3002508023	30902882	MALJAMAR	S 17	E 32	18	MITCHELL B 34			MG/L	198900	3200	1180	-3	-3	68800	220	2000	123000	-0.03	0.99	
1454495.128	10956252.4	3002507964	30902869	HOBBS EAST	S 18	E 39	32	LOWE-STATE 1			MG/L	16001	1076	489	-3	-3	4004	1841	543	8048	-4.22E-04	0.94	
1451418.694	10956328.24	3002507962	30902866	HOBBS EAST	S 18	E 39	31	PEARL GOODE 3			MG/L	18525	766	392	-3	-3	5352	1895	1653	8467	-1.37E-03	0.94	
1448432.451	10960042.84	3002507953	30902861	HOBBS EAST	S 18	E 39	30	SAMUEL E CAIN 4	DST		MG/L	20370	534	186	-3	-3	6520	3120	1060	8950	1.99E-04	0.92	
1454584.657	10959890.9	3002507946	30902852	HOBBS EAST	S 18	E 39	29	BROWNING 1	WELLHEAD OR WELL BLEEDER		MG/L	40849	7830	2830	-3	-3	2686	2138	1405	23960	7.22E-04	0.97	
1455032.314	10978083.76	3002507930	30902849	CARTER	S 18	E 39	7	STEVE TAYLOR B 1			MG/L	18369	1056	444	-3	-3	4801	2040	2314	7714	-1.67E-03	0.94	
1458106.792	10978008.25	3002507919	30902844	CARTER SOUTH	S 18	E 39	5	BURTON-FEDERAL 1			MG/L	17546	1218	616	-3	-3	4080	2091	2030	7511	1.16E-03	0.93	
1435579.178	10938519.7	3002507698	30902770	HOBBS	S 19	E 38	15	FRANK SELMAN 2	DST		MG/L	40031	690	109	-3	-3	14260	2883	649	21440	-7.47E-04	0.96	
1429699.56	10949590.06	3002507669	30902764	HOBBS	S 19	E 38	9	STATE 8			MG/L	10286	967	391	-3	-3	2054	1650	619	4605	-1.59E-04	0.91	
1426530.056	10946029.77	3002507666	30902763	HOBBS	S 19	E 38	9	ORA B TERRY A 1			MG/L	11690	400	600	-3	-3	2850	1240	1600	5000	-3.48E-03	0.94	
1420561.609	10953463.44	3002507648	30902751	HOBBS	S 19	E 38	6	STATE H 2	SWAB		MG/L	34335	926	502	-3	-3	11400	1612	595	19300	7.86E-04	0.97	
1423638.3	10953384.83	3002507624	30902743	HOBBS	S 19	E 38	5	MCKINLEY 1			MG/L	12129	580	281	-3	-3	3593	562	130	6983	-9.83E-04	0.97	
1426714.999	10953306.5	3002507614	30002783	HOBBS	S 19	E 38	5	H D MCKINLEY #3	FROM BRADENHEAD	11/12/1953	MG/L	18172	1253	374	5194	-3	-3	73	0	11278	3.69E-04	0.99	7.14
1435725.152	10950814.17	3002507595	30902726	HOBBS	S 19	E 38	3	WS Capps	DST		MG/L	25470	3400	1220	-3	-3	4170		1700	14400			
1435945.137	10953073.15	3002507587	30902723	HOBBS	S 19	E 38	3	BYERS A 11	FLOWING		MG/L	10450	1210	337	-3	-3	1945	1532	789	4637	1.09E-03	0.92	
1429883.85	10956866.85	3002507562	30902713	BOWERS	S 18	E 38	33	STATE G 3	SEPARATOR, HEATER-TREATER, OR WATER DUMP		MG/L	8880	91	87	-3	-3	3074	787	547	4294	2.55E-05	0.95	
1420747.863	10960740.23	3002507480	30902706	HOBBS	S 18	E 38	30	STATE 2			MG/L	17737	974	218	-3	-3	4872	2335	2030	7308	-0.01	0.93	
1423823.9	10960661.64	3002507449	30902703	HOBBS	S 18	E 38	29	FEDERAL-BOWERS A 7	SWAB		MG/L	45446	5408	3880	-3	-3	5418	1434	3096	26210	-9.41E-04	0.98	
1426899.945	10960583.32	3002507420	30000498	HOBBS	S 18	E 38	28	W. D. GRIMES #1		4/13/1955	MG/L	15631	1233	246	3753	223	-3	1418	2647	6112	2.03E-04	0.95	6.51
1427084.893	10967860.24	3002507380	30902696	HOBBS	S 18	E 38	20	MCKINLEY B 1			MG/L	9763	343	122	-3	-3	3004	2107	14	4173	0.01	0.88	
1425503.046	10966527.89	3002507373	30902692	HOBBS	S 18	E 38	20	Bowers B	DST		MG/L	18873	409	171	-3	-3	6030		253	8050			
1426992.418	10964221.77	3002507373	30902692	HOBBS	S 18	E 38	20	BOWERS B 3	DST		MG/L	18873	409	171	-3	-3	6030	3960	253	8050	-4.57E-04	0.89	
1420934.12	10968017.12	3002507360	30902686	HOBBS	S 18	E 38	19	BOON HARDIN 1	SWAB		MG/L	60301	10230	5000	-3	-3	4697	1046	628	38700	2.59E-03	0.99	
1421027.249	10971655.61	3002507352	30902683	HOBBS	S 18	E 38	18	HARDIN B 2	WELLHEAD OR WELL BLEEDER		MG/L	12835	1479	48	-3	-3	3219	1006	1771	5312	0.03	0.95	
1417952.2	10971734.45	3002507351	30902680	HOBBS	S 18	E 38	18	HARDIN B 1			MG/L	58706	7966	2111	-3	-3	10810	71	2808	34940	-1.17E-03	0.99	
1445808.92	10978311.96	3002507331	30902672		S 18	E 38	12	SINCLAIR-WILLIAMS 1	DST		MG/L	200894	2150	850	-3	-3	75000	354	4530	118000	2.42E-03	0.99	
1433511.159	10978620.09	3002507319	30902670		S 18	E 38	4	HB FUQUA 1	DST		MG/L	35570	850	90	-3	-3	12550	1980	500	19600	6.33E-04	0.97	

Appendix A-3 Table 1
Inorganic Chemistry Data
Research Partnership to Secure Energy for America

EASTING	NORTHING	API NUMBER	UNIQUE ID	FIELD	SUR/TWP	BLK/RNG	SECTION	LEASE NAME	METHOD	SAMPLE DATE	UNITS	TDS	Ca	Mg	Na	K	Na+K	H_2CO_3	SO_4	Cl	CHARGE BALANCE	MASS BALANCE	pH
1442825.311	10982027.19	3002507316	30902668		S 18	E 38	2	B KEOHANE 1	FLOWING		MG/L	306639	3600	5144	-3	-3	108700	137	258	188800	6.64E-04	0.99	
1445029.104	10983810.9	3002507315	30902664		S 18	E 38	1	Tomlinson	DST		MG/L	28910	880	365	-3	-3	9315		5000	13200			
1427639.753	10989691.62	3002507314	30000496		S 17	E 38	32	STATE 709 #1		6/11/1956	MG/L	29468	1600	467	8636	-1	-3	1083	2716	14915	-5.59E-04	0.97	7.08
1440936.446	11029408.35	3002507281	30902646	GARRETT	S 16	E 38	23	PEOPLES SECURITY CO 1			MG/L	75230	2651	726	-3	-3	24820	1241	2662	43130	-7.35E-03	0.99	
1437866.588	11029485.4	3002507280	30902645	GARRETT	S 16	E 38	22	COOPER 1			MG/L	133972	14160	4117	-3	-3	30740	264	1471	83220	7.80E-04	0.99	
1461390.888	11236497.72	3002507085	30902565		S 10	E 38	5	UNION-FEDERAL 1			MG/L	250483	9240	3650	82468	-3	-3	835	1790	152500	3.69E-04	0.99	
1424310.925	10858716.42	3002506984	30902542	BRUNSON	S 21	E 37	33	EO CARSON 13	WELLHEAD OR WELL BLEEDER		MG/L	6725	261	145	-3	-3	2006	652	602	2979	0.02	0.93	
1415335.657	10869866.29	3002506665	30902453	DRINKARD	S 21	E 37	19	LG WARLICK 1	SWAB		MG/L	134673	5608	2182	-3	-3	43420	791	3055	79530	6.81E-03	0.99	
1388445.592	10903331.14	3002506169	30902357	EUNICE	S 20	E 37	19	QUAPAW 1			MG/L	91120	11600	7668	-3	-3	11280	0	722	59850	-1.03E-04	0.99	
1388638.37	10910607.09	3002506163	30902356	MONUMENT	S 20	E 37	18	MEXICO-FEDERAL 1	SEPARATOR, HEATER-TREATER, OR WATER DUMP		MG/L	10070	515	283	-3	-3	2671	1290	746	4566	-8.90E-04	0.93	
1385557.833	10910688.84	3002506159	30902355	MONUMENT	S 20	E 37	18	HOBBS-FEDERAL 1	SEPARATOR, HEATER-TREATER, OR WATER DUMP		MG/L	10194	425	326	-3	-3	2732	1845	98	4768	3.60E-04	0.9	
1391718.914	10910525.61	3002506139	30902354	MONUMENT	S 20	E 37	17	ANDERSON 1			MG/L	111142	3958	591	-3	-3	38300	564	489	67240	-2.38E-04	0.99	
1391814.977	10914163.62	3002506017	30902325	MONUMENT	S 20	E 37	8	BERTIE WHITMIRE 7	WELLHEAD OR WELL BLEEDER		MG/L	65361	2159	432	-3	-3	23850	560	1460	36900	0.04	0.99	
1385751.267	10917964.87	3002505966	30902310	MONUMENT	S 20	E 37	6	BRITT A 1			MG/L	20047	3732	1521	-3	-3	710	3366	2099	8619	5.90E-04	0.91	
1398070.842	10917639.57	3002505890	30902270	MONUMENT	S 20	E 37	4	LAUGHLIN 3			MG/L	23765	2000	875	-3	-3	5400	1590	1500	12400	-1.82E-05	0.96	
1389120.325	10928797.37	3002505756	30902249	EUMONT	S 19	E 37	30	ELLIOTT-STATE 4			MG/L	29080	362	318	-3	-3	10150	2110	60	16080	-3.16E-03	0.96	
1413845.576	10931791.81	3002505689	30902233		S 19	E 37	25	MC NEILL 1	DST		MG/L	305470	1200	2010	-3	-3	115500	260	2500	184000	1.12E-03	0.99	
1389409.505	10939711.82	3002505647	30902226	MONUMENT	S 19	E 37	19	CULP A 7			MG/L	19819	1479	306	-3	-3	5304	592	1938	10200	-0.01	0.98	
1392583.501	10943268.62	3002505620	30902217	MONUMENT	S 19	E 37	17	STATE J 2			MG/L	7029	381	199	-3	-3	1707	2010	50	2680	-9.21E-05	0.85	
1408727.095	10971972.65	3002505458	30902161	HOBBS	S 18	E 37	14	STATE B 3	WELLHEAD OR WELL BLEEDER		MG/L	24217	1565	752	-3	-3	6360	356	2794	12390	4.20E-03	0.99	
1411896.234	10975531.45	3002505449	30902157		S 18	E 37	13	NORTH HOBBS UNIT 1	DST		MG/L	12100	955	271	2623	85	-3	509	2321	4541	4.13E-03	0.91	
1411802.123	10971892.97	3002505440	30902147	HOBBS	S 18	E 37	13	STATE B-13 5	WELLHEAD OR WELL BLEEDER	1/2/1956	MG/L	15670	1335	265	-3	-3	3878	240	2646	7021	2.76E-04	0.97	
1394601.075	11019676.78	3002505388	30902138	LOVINGTON	S 16	E 37	32	STATE P UNIT 2			MG/L	17514	1280	180	-3	-3	4764	1390	2200	7700	4.71E-04	0.95	
1439205.499	11204265.32	3002505009	30901978		S 11	E 37	12	STATE EA 1	DST	5/18/1953	MG/L	226296	3547	925	-3	-3	84450	438	22	136800	8.56E-03	0.99	
1420786.941	11201092.39	3002505008	30901973		S 11	E 37	9	ELEANOR FIFE ETAL 1	DST		MG/L	83126	1740	240	30046	-3	-3	-3	3600	47500	3.11E-04	0.99	
1381215.79	10863479.05	3002504850	30901936	JALMAT	S 21	E 36	31	LOCKHART B-31 1			MG/L	26640	1280	800	-3	-3	7360	1340	2550	13300	5.23E-05	0.97	
1388156.43	10892417.38	3002504513	30901895	EUNICE	S 21	E 36	5	HEASLEY-STATE 3	TANK BATTERY INCLUDING GUNBARREL		MG/L	9090	267	298	-3	-3	2505	1828	192	4000	2.52E-05	0.89	
1376316.267	10910935.78	3002504272	30901876	MONUMENT	S 20	E 36	14	SANDERSON-FEDERAL B-14 2			MG/L	49286	6346	5289	-3	-3	4024	899	1618	31110	1.13E-03	0.99	
1382477.304	10910770.88	3002504259	30901874	MONUMENT	S 20	E 36	13	STATE A 5			MG/L	9936	1080	507	-3	-3	1840	1560	125	4800	0.03	0.91	
1382671.392	10918046.89	3002504235	30901868	MONUMENT	S 20	E 36	12	BYRD 4			MG/L	6973	404	304	-3	-3	1919	644	55	3636	0.05	0.95	
1376609.362	10921849.77	3002504166	30901866	MONUMENT	S 20	E 36	2	STATE A 2	WELLHEAD OR WELL BLEEDER		MG/L	13866	363	295	-3	-3	4339	1604	0	7265	1.29E-04	0.94	
1382768.437	10921684.93	3002504130	30901856	MONUMENT	S 20	E 36	1	PHILLIPS JR 1			MG/L	13609	352	281	-3	-3	4097	615	3330	4934	7.50E-04	0.97	
1367469.487	10925737.14	3002504099	30901852	EUMONT	S 19	E 36	33	NORTHWST EUMONT UNT 33 8			MG/L	68631	2211	848	-3	-3	22740	405	4317	38110	-2.67E-04	0.99	
1360524.391	11009669.54	3002503917	30901824	LOVINGTON WEST	S 17	E 36	8	STATE AH 9	TANK BATTERY INCLUDING GUNBARREL		MG/L	52590	1640	479	-3	-3	17600	1280	3390	28200	5.42E-04	0.98	
1369838.028	11013056.96	3002503867	30901817	LOVINGTON WEST	S 17	E 36	4	WEST LOVINGTON UNIT 4 34	SEPARATOR, HEATER-TREATER, OR WATER DUMP		MG/L	92287	3396	875	-3	-3	30890	400	2666	54060	1.79E-04	0.99	
1382220.8	11016364.61	3002503836	30901796	LOVINGTON	S 17	E 36	1	STATE E TR-18 3			MG/L	28126	1212	2323	-3	-3	5757	1242	2242	15350	2.52E-03	0.97	
1385194.775	11012643.87	3002503834	30901795	LOVINGTON	S 17	E 36	1	STATE E TR-18 1	SEPARATOR, HEATER-TREATER, OR WATER DUMP		MG/L	25396	980	344	-3	-3	8070	160	2802	13040	-1.63E-04	0.99	
1395850.203	11066982.89	3002503696	30901747	DEAN	S 15	E 36	23	SUE ALVA ROBINSON 1	DST		MG/L	21439	1350	780	-3	-3	5379	330	3200	10400	5.40E-04	0.99	
1383681.73	11070948.07	3002503682	30901735	CAUDILL	S 15	E 36	16	STATE GA 1	DST	12/7/1954	MG/L	194836	2155	543	-3	-3	72910	702	4426	114100	1.05E-03	0.99	
1409615.873	11241454.31	3002503632	30901708	CROSSROADS	S 9	E 36	34	SAWYER UD 4			MG/L	298844	20900	2400	-3	-3	91000	244	200	184000	8.60E-04	0.99	
1397702.112	11252697.34	3002503583	30901672	CROSSROADS	S 9	E 36	20	SANTA FE F 1			MG/L	244439	7549	1922	-3	-3	84810	635	423	149100	7.17E-04	0.99	
1397798.573	11256338.05	3002503581	30901670	CROSSROADS	S 9	E 36	20	RE FLAKE 1			MG/L	277245	6950	3292	-3	-3	96140	645	918	169300	2.57E-04	0.99	
1413330.448	11266859.94	3002503552	30901650	ALLISON	S 9	E 36	2	ADAMS-STATE 1	SWAB		MG/L	225250	12000	5350	-3	-3	73400	-3	1500	133000	0.05	0.99	
1327068.156	10974906.99	3002503121	30000555		S 18	E 35	17	State Lea 401	DST #4	18-Jun-56	MG/L	205411	8053	2317	64582	-1	-3		1449	128779			7.3
1329293.685	10992332.7	3002502936	30901498	VACUUM	S 17	E 35	29	STATE F 1	SEPARATOR, HEATER-TREATER, OR WATER DUMP		MG/L	13368	748	234	-3	-3	3589	1395	2204	5176	-4.76E-03	0.94	
1344963.684	11002816.71	3002502856	30901491		S 17	E 35	22	STATE AC 1	DST		MG/L	101486	2990	1560	-3	-3	33900	366	2570	60100	2.45E-05	0.99	
1354381.136	11009838.39	3002502817	30901490	LOVINGTON WEST	S 17	E 35	12	STATE V 1	PRODUCTION AND DEVELOPMENT TEST		MG/L	28048	1218	2335	-3	-3	5786	1248	2253	15200	8.97E-03	0.97	
1373403.119	11256993.19	3002502659	30901440	JENKINS	S 9	E 35	16	KING-STATE 1			MG/L	223452	13510	5714	-3	-3	64630	608	1590	137400	5.48E-03	0.99	
1310644.85	10985582.85	3002502284	30901305	VACUUM	S 18	E 34	3	STATE X NCT-1 4			MG/L	202520	2480	950	-3	-3	75000	840	5250	118000	2.66E-03	0.99	
1307781.522	10992948.15	3002502135	30901296	VACUUM	S 17	E 34	27	STATE D 3			MG/L	246592	2497	879	-3	-3	92240	-3	4971	145600	6.82E-04	0.99	
1313927.815	10992770.93	3002502121	30901295	VACUUM	S 17	E 34	26	BRIDGES-STATE 26			MG/L	206983	2120	898	-3	-3	77400	165	3400	123000	1.31E-03	0.99	
1314136.977	11000047.6	3002502072	30901290	VACUUM	S 17	E 34	23	STATE VA 3			MG/L	124371	3888	2862	-3	-3	39420	311	2290	75600	-8.69E-03	0.99	
1317417.993	11007236.22	3002502043	30901287	VACUUM	S 17	E 34	14	BRIDGES-STATE 70	WELLHEAD OR WELL BLEEDER		MG/L	138735	5193	2924	-3	-3	44180	327	2651	83460	2.18E-03	0.99	
1314241.56	11003685.98	3002502030	30901286	VACUUM	S 17	E 34	14	BRIDGES-STATE 34	WELLHEAD OR WELL BLEEDER		MG/L	132985	5597	3038	-3	-3	41270	240	2668	80150	1.67E-03	0.99	
1320593.781	11010786.78	3002502016	30901285	VACUUM	S 17	E 34	12	BRIDGES-STATE 88	WELLHEAD OR WELL BLEEDER		MG/L	227581	36090	10310	-3	-3	34450	120	111	146500	2.09E-03	0.99	
1337690.673	11072210.05	3002501879	30901238		S 15	E 34	13	M ARREGUY 1	DST		MG/L	215835	1820	455	-3	-3	82000	560	2000	129000	1.59E-03	0.99	
1345448.69	11239548.77	3002501813	30901201		S 10	E 34	3	STATE NLA 1			MG/L	14481	2599	1193	-3	-3	588	559	3365	6177	-1.58E-05	0.97	
1262125.926	11008865.34	3002501468	30901144	MALJAMAR	S 17	E 33	18	MALMAR UNIT TR-1 3			MG/L	55982	3001	1084	-3	-3	16770	369	2668	32090	1.53E-03	0.99	
1255760.934	11001775.47	3002500660	30900902	MALJAMAR	S 17	E 32	24	JOHNS B 2			MG/L	221103	2090	1336	-3	-3	82790	187	-3	134700	2.54E-03	0.99	
1237439.776	11005979.96	3002500592	30900887	MALJAMAR	S 17	E 32	17	MITCHELL-FEDERAL B 9		9/2/1954	MG/L	109034	2050	309	-3	-3	39810	647	1478	64740	-1.39E-03	0.99	
1253021.967	11012783.8	3002500508	30900869	ROBERTS WEST	S 17	E 32	11	WB TRIMBLE B 3	SEPARATOR, HEATER-TREATER, OR WATER DUMP		MG/L	19817	1790	463	-3	-3	4729	681	2848	9306	5.57E-04	0.98	
1273416.298	11179709.54	3002500083	30900793	CAPROCK EAST	S 12	E 32	2	STATE ECA 1	DST		MG/L	142493	2041	350	-3	-3	52640	183	6079	81200	8.61E-04	0.99	

Appendix A-3 Table 1
Inorganic Chemistry Data
Research Partnership to Secure Energy for America

EASTING	NORTHING	API NUMBER	UNIQUE ID	FIELD	SUR/TWP	BLK/RNG	SECTION	LEASE NAME	METHOD	SAMPLE DATE	UNITS	TDS	Ca	Mg	Na	K	Na+K	H_2CO_3	SO_4	Cl	CHARGE BALANCE	MASS BALANCE	pH
1261966.864	11205557.54	3002500051	30900787		S 11	E 32	16	AMERADA-STATE 1	DST		MG/L	22056	1999	24	-3	-3	5916	2122	2203	9792	3.42E-03	0.95	
1283996.6	11226753.09	3002500024	30900783	MESCALERO	S 10	E 32	22	STATE AD 2			MG/L	286025	2640	145	-3	-3	109000	890	3200	170000	1.71E-03	0.99	
1287156.959	11230302.3	3002500019	30900781	MESCALERO	S 10	E 32	14	STATE BL 1	DST		MG/L	239624	2400	754	-3	-3	88700	1270	2500	144000	-0.01	0.99	
1290424.583	11237492.03	3002500015	30900780		S 10	E 32	11	GULF-STATE 1	DST		MG/L	281677	2320	2680	-3	-3	103600	713	4164	168200	8.20E-04	0.99	
1285407.982	11274076.93	3002500002	30900773		S 9	E 32	3	MAGNOLIA-STATE 1	DST		MG/L	92491	2502	643	-3	-3	32750	925	4791	50880	0.01	0.99	
1046351.199	10910462.21	3001505919	30900574		S 20	E 26	29	SEVEN RIVERS HILLS UNT 42			MG/L	117506	2021	704	-3	-3	42240	2236	3655	66650	1.61E-03	0.99	
1209792.423	11006848.05	3001505171	30900478	GRAYBURG-JACKSON	S 17	E 31	16	STATE B 2	WELLHEAD OR WELL BLEEDER		MG/L	213713	12580	7322	-3	-3	58570	183	1258	133800	-2.55E-03	0.99	
1154378.28	11005013.48	3001503042	30002786	GRAYBURG-JACKSON	S 17	E 29	22	M DODD A NO 8	BLEEDER PUMPING UNIT		MG/L	178711	2727	749	65152	585	-3	402	4600	104425	6.14E-04	0.99	6.8
1151915.819	11023305.74	3001502873	30900359	SQUARE LAKE	S 17	E 29	3	EDDY-STATE 2	WELLHEAD OR WELL BLEEDER		MG/L	109000	1796	716	-3	-3	39230	339	3538	63070	-1.09E-04	0.99	
1112932.356	10962721.19	3001502178	30900305	ARTESIA	S 19	E 28	4	MRY-STATE 1			MG/L	140946	4809	3898	-3	-3	43920	450	2229	85640	1.13E-03	0.99	
1104085.267	10973953.82	3001501942	30900303	ARTESIA	S 18	E 28	19	ARTESIA-STATE 2	WELLHEAD OR WELL BLEEDER		MG/L	249200	3277	1878	-3	-3	90690	0	5974	146800	5.50E-04	0.99	
1121712.959	11038900.12	3001501262	30900286	CROW FLATS	S 16	E 28	22	MCWHORTER 1			MG/L	171908	2643	1089	-3	-3	62720	287	3069	102100	1.01E-03	0.99	
1099866.203	10941325.41	3001501004	30900262		S 19	E 27	25	STATE 1			MG/L	187505	2650	850	-3	-3	68930	475	5600	109000	1.04E-03	0.99	
1085893.916	10981876.75	3001500898	30900244	EMPIRE	S 18	E 27	15	MALCO REFINING-FED N 1	BAILER INCLUDING TRIP SAMPLER		MG/L	326942	2538	573	-3	-3	124500	231	5800	193300	1.94E-03	0.99	
1070914.609	10993336.54	3001500802	30900217	RED LAKE	S 18	E 27	6	WM STERLING JR 1			MG/L	225206	3266	1679	-3	-3	82220	781	2760	134500	2.56E-03	0.99	
1094092.278	11039861.83	3001500564	30900205		S 16	E 27	23	HITCHCOCK-FEDERAL 23 1			MG/L	183046	3640	1360	65547	-3	-3	-3	3500	109000	3.85E-04	0.99	
1055021.027	10979341.64	3001500214	30900164	ATOKA	S 18	E 26	21	MILDRED LEE 1			MG/L	222545	2040	510	-3	-3	83800	354	3840	132000	-1.83E-03	0.99	
1388133.378	11266906.19		30002304		S 09	E 35	12	Betenbough	DST	1-Mar-50	PPM	96542	1401	800	34816	-3	-3		2226	56514			6.3
1433829.546	10942422.81		30001665	HOBBS	S 19	E 38	15	STATE A TRACT 9 1-SWD	DST NO. 2	24-Jul-57	MG/L	40120	690	109	14225	-3	-3		649	21465			7
1398711.756	11266624.47		30002307		S 09	E 36	8	Walker -Federal	DST		PPM	247762	6579	2700	86033	-3	-3		1609	150982			6.7
1968808.035	10343518.93		42105704	FARMER				CITIES SERVICE UNIV 1		12/8/1956	MG/L	320713	1746	1720	-3	-3	123900	535	4012	188800	0.01	0.99	6.3
1869405.221	10410068.74		42105607	BIG LAKE				UNIVERSITY # 184	FORMATION TEST - L - 6	9/5/1957	MG/L	169624	6566	99	-3	-3	58001	1148	2290	101520	-0.01	0.99	6.5
1676733.835	10474812.78		42105667	MCELROY				SINCLAIR #6		10/19/1956	MG/L	68965	2520	2041	-3	-3	20685	753	4746	38220	2.44E-03	0.99	7
1492932.897	10489497.5		42011274	WARD SOUTH				MILLER #2	WELLHEAD	6/13/1949	MG/L	4738	497	140	885	-3	-3	1106	807	1414	-9.85E-04	0.9	7.4
1712830.513	10579688.62		42105562	SWEETIE PECK				SAN ANDRES #1		9/14/1950	PPM	77000	2260	880	-3	-3	25000	336	4600	42000	-4.51E-03	0.97	7.2
1588571.909	10589285.15		42011534	JORDAN				UTEX A #7	WELLHEAD	12/28/1949	MG/L	40781	1449	421	13157	-3	-3	1831	3469	20454	6.14E-04	0.97	7.2
1641708.496	10602791.77		42105421	COWDEN SOUTH				TXL CONTINENTAL 43-13		7/3/1953	MG/L	91734	2842	1603	-3	-3	29740	893	3877	52780	-4.59E-03	0.99	7
1735429.738	10630249.9		42105500	PARKS				PARKS UNIT W I W 13-3		1/30/1957	MG/L	92852	4197	644	-3	-3	30528	667	2544	54272	-6.39E-04	0.99	6.1
1549881.208	10670149.84		42011551	T X L				JOHNSON #3	SEPARATOR	11/13/1953	MG/L	47241	1593	500	15501	-3	-3	605	4646	24396	6.66E-04	0.99	8
1562909.036	10698981.52		42011546	GOLDSMITH				RUMSEY A - 7	WELL HEAD	5/23/1949	MG/L	100850	1872	323	36468	-3	-3	346	5948	55892	7.99E-04	0.99	7.9
1538272.736	10706792.61		42006859	GOLDSMITH NORTH				J. M. WILLIAMSON LSE.	STOCK TANK BLEEDER	7/12/1957	MG/L	104105	3129	1357	34330	961	-3	203	3623	60503	8.58E-04	0.99	6.98
2009628.706	10732392.45		42252848	HOWARD-GLASSCOCK				HART PHILLIPS #9	AT WELLHEAD	6/13/1957	MG/L	76316	2634	1014	25229	-3	-3	1014	1903	44521	8.28E-04	0.99	5.57
1656777.175	10744417.34		42105734	MIDLAND FARMS				FASKIN AA #2		10/15/1952	MG/L	70769	2912	905	-3	-3	22568	1622	4075	38688	1.54E-04	0.98	7.4
2016088.722	10765086		42252868	SNYDER				T P LAND TRUST #2	DST	1/10/1955	MG/L	106103	2215	573	37915	-3	-3	107	4949	60344	7.49E-04	0.99	7.19
1573888.972	10778810.46		42105730	FUHRMAN-MASCHO				FORD 11		3/19/1954	MG/L	62166	2090	1778	-3	-3	18800	1774	3448	34276	9.78E-04	0.98	7.35
1577590.146	10807848.13		42105763	DEEP ROCK				OGDEN 2		8/25/1956	MG/L	27284	1258	468	-3	-3	7917	1198	5075	11368	9.88E-06	0.97	8
1559598.025	10833706.39		42105742	SHAFTER LAKE				NOLA FISHER D NO 1		7/1/1955	MG/L	42902	1987	1307	-3	-3	12213	1106	2691	23598	-6.42E-04	0.98	7.8
1433109.199	10840293.65		30002134	PENROSE-SKELLY				GRIZZELL #1	WELLHEAD	5/27/1951	MG/L	20168	266	444	6145	-3	-3	656	1860	9492	2.07E-04	0.91	8.3
1621705.877	10850627.79		42019434	MCFARLAND				VANLANDINGHAM #1-34		8/30/1955	MG/L	292184	2656	9709	-3	-3	96695	219	5825	177080	2.55E-03	0.99	7
1606568.932	10865487.58		42018298	MEANS				J. S. MEANS G 3	DST NO. 2	6/12/1955	MG/L	32237	1386	423	9977	-3	-3	1063	3558	15831	4.04E-04	0.98	6.8
1444179.766	10912820.96		30001256		S 20	E 38	12	DAISY BLANKENSHIP #1		4/16/1955	MG/L	60898	1753	584	20210	710	-3	285	3362	33963	7.80E-04	0.99	7.83
1518275.196	10918338.44		42011267	JENKINS				SANGER WELL #1	TEST TANK	6/22/1951	MG/L	74201	5813	3477	17157	-3	-3	841	2012	44901	8.02E-04	0.99	7.2
1555312.518	10921157.29		42105457	ROBERTSON			20	MORROW #1		2/23/1937	PPM	38980	1420	542	-3	-3	11847	1086	3416	18700	0.01	0.93	7.8
1388927.541	10921521.19		30002027	MONUMENT				CRUTCHFIELD #1		3/25/1949	MG/L	5391	262	192	1685	-3	-3	1426	13	2784	-3.76E-04	1.04	7.5
1420468.483	10949825.09		30001662	HOBBS	S 19	E 38	6	STATE H NO. 2	WELLHEAD SWAB	2/12/1957	MG/L	34346	926	502	11406	-3	-3	1616	595	19301	9.30E-04	0.97	7.1
1451508.551	10959966.73		30001129	HOBBS				W. D. GRIMES #1		5/4/1954	MG/L	13129	880	218	3474	-3	-3	787	2350	5420	-4.01E-03	0.96	6.8
1571789.932	10971769.67		42105459	SEMINOLE				PARKER #1	WELL	1/1/1954	MG/L	44954	1483	700	-3	-3	14420	891	3564	23896	-2.02E-03	0.98	7.32
1621063.21	10974401.59		42105455	HOMANN				HOMANN #1		11/14/1943	PPM	37804	1756	467	-3	-3	11904	780	3665	19200	0.01	0.98	
1725974.08	10994332.52		42105682	CEDAR LAKE SE				LESHERE 1-122		8/3/1953	MG/L	85647	3808	1926	-3	-3	26027	1102	3269	49514	-1.87E-06	0.99	7.45
1710796.223	11005510.64		42105541	CEDAR LAKE				TANK BATTERY		2/29/1956	PPM	71399	2440	972	-3	-3	23400	1195	2992	40400	-5.15E-05	0.99	7.6
1511461.371	11024073.09		42105458	RUSSELL				JONES #1	DST	7/28/1944	PPM	39035	4250	-2	-3	-3	10416	211	2474	21648	1.23E-04	0.99	7.8
1738801.15	11026885.28		42018890	WELCH NORTH				D. D. LATTIMORE #1	SEPARATOR	7/1/1955	MG/L	80496	3830	1501	24749	-3	-3	682	2816	46920	-3.87E-05	0.99	7.5
1699145.193	11042118.95		42006835	ADAIR				JONES B #3	SEPARATOR	4/18/1949	MG/L	61725	2376	610	20225	-3	-3	1004	3542	33969	7.40E-04	0.99	7.4
1530782.155	11063687.01		42011247	WASSON				KELLER #15	SEPARATOR	8/21/1949	MG/L	216983	3809	913	80913	-3	-3	783	3344	127222	0.01	0.99	6.7
1598853.069	11240679.06		42009575	SLAUGHTER						1/1/1953	MG/L	262481	20945	5043	72587	-3	-3	674	1096	162137	1.91E-03	0.99	
1633125.561	11276419.41		42105586	LEVELLAND				BEASLEY 8		12/8/1954	PPM	226968	18625	8510	55834	-3	-3	-3	-3	144000	3.75E-04	0.99	6.3
1655493.938	11330636.41		42015586	YELLOWHOUSE				TOM COBB A R/A B #7	BLEED ON WELLHEAD	12/14/1955	MG/L	321203	57919	10198	47489	-3	-3	304	385	204908	9.31E-04	0.99	6
1436286.173	10720105.01		30001314		S 26	E 37	12				MG/L	5410	25	77	1776	-3	-3	1165	161	2209	-9.22E-05	0.88	
1439101.298	10832863.56		30001296		S 22	E 37	25				MG/L	20944	230	368	6990	-3	-3	1807	1361	10188	1.12E-03	0.95	
1449531.844	10879925.49		30001290		S 21	E 38	8				MG/L	78215	4205	1643	23059	-3	-3	1365	3633	44310	7.62E-04	0.99	
1435762.156	10945796.38		30001457		S 19	E 38	10				MG/L	31954	235	141	11846	-3	-3	1252	400	18081	4.03E-04	0.97	
1429607.416	10945951.7		30001330		S 19	E 38	9		BAILER		MG/L	55648	1250	9897	4743	-3	-3	1677	2580	35501	8.61E-04	0.98	7.4

Appendix A-3 Table 1
Inorganic Chemistry Data
Research Partnership to Secure Energy for America

EASTING	NORTHING	API NUMBER	UNIQUE ID	FIELD	SUR/TWP	BLK/RNG	SECTION	LEASE NAME	METHOD	SAMPLE DATE	UNITS	TDS	Ca	Mg	Na	K	Na+K	H_2CO_3	SO_4	Cl	CHARGE BALANCE	MASS BALANCE	pH
1435853.646	10949434.75		30001322		S 19	E 38	3				PPM	25420	2493	634	5701	-3	-3	2135	2527	11930	8.94E-04	0.95	
1423545.502	10949746.47		30001449		S 19	E 38	5				MG/L	-3	915	798	2256	-3	-3	1347	1998	3471	0.12		
1414595.81	10960898.25		30001283		S 18	E 37	25				MG/L	18503	177	408	5893	-3	-3	3363	123	8540	6.51E-04	0.9	
1224467.586	10984534.86		30001272		S 18	E 31	12				MG/L	205572	9116	2160	67351	-3	-3	114	2410	124423	8.94E-04	0.99	
1110865.782	10991927.53		30001273		S 18	E 28	5				MG/L	225285	2624	504	84002	-3	-3	288	5692	131670	-6.09E-04	0.99	
1295595.576	10996944.18		30001280		S 17	E 34	30				MG/L	235687	2960	1277	86833	-3	-3	588	5847	138182	9.10E-04	0.99	
1388169.412	11008923.4		30001281	LOVINGTON	S 17	E 37	7				MG/L	52746	1675	534	17594	-3	-3	1087	3212	28645	7.34E-04	0.98	
1274073.498	11201547.87		30001270		S 11	E 32	14				MG/L	338687	5437	1333	116663	-3	-3	71	3605	191484	-1.16E-03	0.94	
1399598.368	11208930.75		30001271		S 11	E 36	2				MG/L	305064	2657	1360	114449	-3	-3	428	5405	180765	1.25E-03	0.99	
1401040.308	11263538.91		30002308		S 9	E 36	8	MAGNOLIA #1 WALKER - FEDERAL	DST		PPM	271567	2965	2320	99336	-3	-3	197	2296	163433	7.08E-04	0.99	7.3
2032341.472	10866846.04		42009264	CORONET							MG/L	84222	3285	1135	21785	-3	-3	758	2240	55019	-0.14	0.99	7.3
2103899.963	10975553.92		42009270	KELLY-SNYDER							MG/L	116319	6651	2611	34286	-3	-3	711	1319	70742	1.65E-03	0.99	7.3
1531896.241	10976278.86		42009310	SEMINOLE WEST							MG/L	62193	1031	405	22034	-3	-3	1203	4720	32800	6.75E-04	0.99	7.7

TDS	Total dissolved solids	Na+K	Sodium Potassium
Ca	Calcium	H_2CO_3	Bicarbonate
Mg	Magnesium	SO_4	Sulfate
Na	Sodium	Cl	Chloride
K	Potassium		

APPENDIX B
Contact Elevations

Appendix B Table 1

Contact Elevations for Upper, Lower, and Porosity Zones for the San Andres

Research Partnership to Secure Energy for America

EASTING	NORTHING	API NUMBER	FIELD	SUR/TWP	BLK/RNG	SECTION	SPOT LOCATION	OPERATOR	WELL	LEASE NAME	COMPLETION DATE	DTM ELEVATION	Psa	Pgl/Pco	ϕ (Top)	ϕ (Base)	TD
1471744.60	10630787.08	4249531587		PSL	B6	25	3107fsl&3289fwl	KIMBARK	1	Carter (A.G.) Foundation	9/28/1983	2868.5	-1139.5	-2271.5	-1393.5	-1616.5	9955
1464565.54	10617717.42	4249510793	Wildcat D&A	PSL	B11	9	1980fnl&1980fel	BROWN (Tom) Drilling	1	Hogg	9/19/1966	2822	-1058	-2184	-1158	-1570	6250
1477712.08	10601050.82	4249510713	Monahans North	G&MMB&A	A	70	660fnl&660fwl	PAN AMERICAN PETROLEUM	4	Sealy-Smith Foundation B	12/30/1965	2777	-1062	-2203	-1193	-1723	10318
1498825.24	10575912.79	4249510411	MONAHANS NORTH	G&MMB&A	A	45	990fsl&1980fel	ASHMUN-HILLIARD & TENNECO	1	Sealy-Smith	3/26/1963	2727	-843	-1943	-1061	-1425	10983
1467860.76	10616033.53	4249510310	KERMIT SE	PSL	B11	10	660fsl&660fwl	SINCLAIR OIL & GAS	1	Hogg (J.C.)	6/11/1965	2816	-1072	-2251	-1219	-1598	12455
1461526.72	10623823.92	4249510212	Wildcat D&A	PSL	B11	2	660fnl&1980fwl	LONE STAR PRODUCTION	1	Hogg (Fay H.)	3/9/1965	2835.6	-1062.4	-2224.4	-1229.4	-1614.4	9700
1479839.03	10585095.77	4249510083	DARMER	G&MMB&A	A	74		EASTLAND OIL	1	SEALY-SMITH 1	4/23/1964	2720	-1064	-2183	No Log Signature	-1580	10331
1449264.72	10676968.05	4249510051	Keystone	PSL	B3	2	1980fsl&1980fel	CARTER FOUNDATION	15	Pure-Walton E	1/25/1965	2964	-541	-2016	-926	-1246	9930
1476475.98	10595221.77	4249505680	Halley South	G&MMB&A	A	72	660fnl&1980fel	TEXAS & PACIFIC COAL & OIL	1	Sealy-Smith Foundation B	6/26/1962	2749	-1033	-2206	No Log Signature	-1571	10028
1458184.48	10629803.48	4249505508	Emperor Devonian	PSL	B5	19	660fsl&660fwl	TEXACO	1	Thomas (J.A.) Unit	5/22/1960	2857	-1070	-2250	-1253	-1603	9700
1454922.20	10660421.01	4249505448	KERMIT SOUTH	PSL	B3	21	660fnl&760fwl	SUPERIOR OIL	1	Walton (J.C.) A	3/20/1957	2922	-908	-2016	No Log Signature		10690
1450368.74	10619393.94	4249505387	Emperor Holt	PSL	B11	4	660fwl&1780fnl	SUN OIL	15	Halley (S.M.) B	6/6/1952	2813	-507	-1947			4843
1468687.75	10598245.55	4249504454	HALLEY	G&MMB&A	A	90		SINCLAIR OIL & GAS	1	SEALY & SMITH FND.	8/23/1957	2752	-895	-2020	-1073	-1448	12124
1488851.82	10582242.50	4249504395	Wildcat D&A	G&MMB&A	A	55	660fnl&660fwl	SHELL OIL	52	Sealy-Smith Foundation	10/12/1952	2724	-1071	-2186	-1224	-1716	5250
1472736.62	10636811.22	4249503369	Wildcat D&A	PSL	B6	17	660fwl&1980fnl	PAN AMERICAN	1	Milmo (Etta L.)	5/28/1961	2888	-1144	-2222	-1382	-1625	10270
1480829.10	10585385.33	4249502502	Wildcat D&A	G&MMB&A	A	74	660fnl&660fel	JOHNSTONE (Carl, Jr.)	1	Sealy & Smith Foundation	3/24/1959	2719	-1071	-2187	-1231	-1763	6300
1478865.71	10620625.57	4249501898	Wildcat D&A	PSL	B10	7	1980fsl&1980fwl	GOLDSTON OIL	1	Hogg-Skelly	10/23/1961	2850	-1110	-2270	-1348	-1600	10307
1441561.24	10620742.41	4249500198	Emperor	PSL	B5	26	1980fsl&1980fel	BARNES (J.C.)	1	Kerr B	6/30/1960	2820	-797	-1915	-1120		9178
1471241.87	10641868.59	4249500171	Jasper	PSL	B6	14	660fwl&1980fnl	ATLANTIC REFINING	1	W.S. Jasper	8/6/1957	2899	-1141	-2351	-1363	-1651	11961
1493588.19	10468056.43	4247510862	Wildcat D&A	H&TCRR	32	13	660fnel&660fnwl	PALM PET & PAGE (Paul)	1	Carr & Smith	4/1/1967	2463	-807	-1922	-1267	-1357	8740
1491719.95	10473116.87	4247510837	Wildcat D&A	H&TCRR	34	7	660fsel&1333fnel	HOLBROOK (F.W.) & PAGE (Paul)	1	Olcott	12/22/1966	2480	-803	-1893	-1270	-1285	8438
1488763.60	10477933.53	4247510734	Ward, South	H&TCRR	34	6	660fswl&1980fsel	STANDARD OF TEXAS	2	Gordon (A.B.) P	2/22/1966	2533	-774	-1885	-1297	-1327	8755
1490640.73	10475437.68	4247510563		PSL	B29	30	467fswl&1100fnwl	HOLBROOK & PAGE(Paul)	1	Maxwell	11/16/1965	2520	-804	-1913	-940	-1290	4899
1495925.86	10487911.11	4247510510	Miller Block B29	H&TCRR	34	4	1856fnwl&1990fswl	SUN OIL	1	Green (Kate S.)	9/24/1964	2551	-877	-1909	-1204	-1269	8155
1524422.91	10540293.68	4247510367	Janelle SE D&A	PSL	B18	17	1980fsl&660fwl	NORSWORTHY (C.L.)	1	Edwards (Jack) C	10/26/1963	2652	-725	-1793	-900	-1238	5500
1517452.88	10472253.14	4247510359	Shiply	H&TCRR	5	15	2173fnwl&467fnel	LUCE (W.P.) & ICE (C.O.)	1	Robeson	7/20/1963	2530	-392	-1230	-456	-735	4050
1536372.15	10482224.24	4247510294	Sand Hills West Devonian	PSL	B28	16	1100fsl&1980fel	GULF OIL	80	Wristen Brothers	3/8/1965	2503	-188	-1321	-504	-937	6245
1532191.93	10519073.48	4247510015	CRAWAR WEST	PSL	B20	14	467fnl&1787fel	BROWN (H.L., Jr.) & HEATH (W.J.)	1	Winter (W.I.)	2/4/1964	2570	-450	-1400	-585	-813	6391
1509487.81	10513407.34	4247510013	HAS	PSL	B19	11	660fsl&660fwl	BRITISH AMERICAN	1	Marston (E.J.) C	11/25/1964	2540	-870	-1880	-1012	-1260	7525
1521884.22	10472059.35	4247505153	Shiply	H&TCRR	5	3	330fnwl&2310fswl	MCGRATH & SMITH	1	Mobil-Hayzlett	7/8/1962	2505	-353	-1208	-434	-729	9250
1532413.50	10524315.07	4247504469	Crawar North	PSL	B20	4	660fsl&660fel	SOUTHLAND ROYALTY	1	Edwards (Janelle) A	9/10/1962	2601	-457	-1479	-569	-839	6480
1508163.05	10567213.67	4247504129	MONAHANS	G&MMB&A	A	38	750fsl&950fel	SHELL OIL	78	Sealy-Smith Foundation	3/6/1957	2711	-794	-1811	-973	-1289	8393
1534770.67	10521094.19	4247503974	Crawar Ellenburger	PSL	B20	8	660fwl&1980fsl	SINCLAIR	3	Tubb (J.B.)	3/15/1957	2582	-583	-1401	-668	-868	8251
1527478.80	10523154.45	4247500732	Wildcat D&A	PSL	B20	5	660fsl&660fel	COX (Edwin L.)	1	Winter (W.I.)	10/13/1958	2567	-611	-1604	-793	-1033	6786
1536125.01	10455550.99	4247500002	Dorr	H&TCRR	4	37	660fnel&660fnwl	ABELL (George T.)	1	Eudaly	11/2/1961	2416	-244	-1094	-312		5900
1636480.38	10312520.49	4237136398	Chenot, East	H&GNRR	11	65	467fsl&467fel	DYAD PETROLEUM	1	Monroe	9/5/1994	2991	1049	463	751	601	5400
1678005.57	10328975.65	4237136074	Wildcat D&A	H&GNRR	12	42	760fwl&1400fnl	PRIMARY FUELS	1	Nevill	5/23/1988	2443	683	243	668	523	5409
1556163.19	10350744.74	4237135575	Mona South	T&StLRR	140	15	660fel&1980fsl	CALLAWAY PRODUCTION	1	Manhatten Fee	11/17/1985	2585	945	180	790	475	4684
1618754.59	10265793.18	4237135533		T&StLRR	125	17	1980fnl&2310fel	YATES (Harvey E.)	2	Page-Hanks 17	7/23/1985	2953	348	-177	283	-107	4850
1557393.94	10350733.15	4237135501	Mona South	T&StLRR	140	14	660fwl&1980fsl	CALLAWAY PRODUCTION	1	Manhatten-State	7/17/1985	2579	895	157	767	471	4785
1568928.45	10363844.77	4237135490	Wildcat D&A	T&StLRR	141	2	467fnl&1200fwl	OMAR OPERATING	2	Arco-State	5/14/1985	2493	723	98	718	293	4615
1620484.82	10265806.92	4237135113	Barbasal	T&StLRR	125	17	660fel&1820fnl	YATES (Harvey E.)	1	Page-Hanks 17	4/1/1985	2893	316	-162	273	-159	7730
1568453.98	10367507.10	4237134668		T&StLRR	141	1	660fwl&1980fnl	NORTH AMERICAN ROYALTIES	2	Auta	6/5/1984	2473	721	88	683	463	5400
1569687.24	10366295.39	4237134582		T&StLRR	141	1	1980fsl&1980fwl	NORTH AMERICAN ROYALTIES	1	Auta	2/8/1984	2486	766	116	726	452	5066
1563266.20	10440764.25	4237134080	T.C.I.	H&TCRR	3	18	467fmeel&2505fmnnl	RAM PETROLEUM	3	Kramer	1/17/1983	2396	-64	-800	-80	-384	6099
1563072.77	10439593.25	4237134069	T.C.I.	H&TCRR	3	18	467fel&3705fnl	RAM PETROLEUM	5	Kramer	3/21/1983	2399	-83	-821	-88	-366	6100
1636535.31	10290730.11	4237134063		UL	19	10	1340fnl&1980fel	SUPERIOR OIL	1	University 19-10	1/1/1983	2645	-101	-460	-107	-285	7118
1563279.26	10437682.56	4237133993	Abell	H&TCRR	3	11	515fnel&816fnwl	STEPHENS (Mickie)	1	Heagy A	1/7/1983	2401	6	-634	-45	-179	3452
1562728.90	10439731.48	4237133610	Abell (West)	H&TCRR	3	18	853fel&3600fnl	RAM PETROLEUM	2	Kramer	12/12/1982	2398	-44	-810	-80	-382	2375
1562902.37	10440844.69	4237133605	Dameron	H&TCRR	3	18	853fel&2450fnl	RAM PETROLEUM	1	Cramer	3/21/1983	2395	-21	-660	-95	-305	4028
1681343.95	10333107.05	4237133223	El Cinco	H&GNRR	12	41	1980fnl&1980fel	TIPPERARY OIL & GAS	1	Tipperary	8/31/1981	2382	662	195	657	502	4502
1734439.32	10291346.88	4237132799	Wildcat D&A	TCRR	Z	36	660fnl&660fwl	YOUNG (Marshall R.)	1	Baker (Mary) et al	7/29/1979	2740	760	195	Zero Porosity		8118
1544314.79	10390775.68	4237132763		H&GNRR	10	64	660fnwl&660fswl	MAGNATEX CORPORATION	2	Sullivan	10/7/1980	2488	408	-242	298	-37	5300
1713460.48	10296707.28	4237132714	Wildcat D&A	GC&SFRR	194	89	850fnl&850fwl	GENERAL CRUDE	1	White & Baker	4/14/1979	2986	741	136	711	431	8000
1551248.33	10376180.22	4237132627	Wildcat D&A	H&GNRR	10	61	660fsel&1980fnel	MAGNA TEX CORPORATION	1	Iowa Realty Trust	6/9/1979	2488	553	-120	468	-22	5200
1557507.84	10379546.39	4237132582	Lehn-Apco	H&GNRR	10	67	660fnel&1980fnwl	LOVELADY (Ike)	1	Iowa Realty Trust	8/3/1978	2468	560	-67	530	238	4860
1647825.58	10315454.08	4237132510	Putnam	H&GNRR	11	47	467fel&1470fnl	GULF OIL	16	Millar (L.H.) et al	5/31/1978	2913	893	428	883	643	5400
1658710.42	10292463.80	4237132385	Wildcat D&A	UL	18	16	660fsl&1980fel	AMOCO PRODUCTION	1	University FE	2/8/1978	2539	-569	-961	-677	-816	6110
1565247.08	10437797.52	4237132363	Abell West D&A	H&TCRR	3	12	1000fswl&2249fwl	ABELL (G.T.)	6	State-Heierman	10/13/1977	2396	-74	-782	-104	-314	5652
1510497.76	10408309.39	4237132345	Wildcat D&A	H&GNRR	10	6	996fnwl&1326fswl	FLAG-REDFERN OIL	1X	Moore-Gilmore	10/4/1977	2482	88	-758	52	-358	9725
1560142.51	10376711.18	4237132330	Lehn-Apco South	Merchant (Mrs. L.)	110	3	467fel&7070fsl	LOVELADY (I.W.)	2	Taft	11/23/1977	2475	625	-75	600	515	4815
1522819.38	10400305.82	4237132307	Wildcat D&A	H&GNRR	10	18	660fsel&2173fnel	HILLIARD OIL & GAS	1	Grant-State	7/26/1977	2526	286	-628	226	-264	5768
1560975.57	10374365.31	4237131805		Merchant (Louise)	110	4	467fwl&4646fsl	LOVELADY (I.W.)	1	Chalkley	1/17/1977	2476	666	26	586	536	4740
1801059.64	10246107.49	4237131789		EL&RRRR	C3	6	660fel&1980fnl	COQUINA OIL	1	J.N.T. (Thigpen, J.N.)	6/7/1977	2295	-88	-775	-265	-295	10670
1540236.54	10394160.11	4237131354	Wildcat D&A	H&GNRR	10	51	660fnwl&660fnel	BAXTER (D.B.)	1	Chalkey	6/18/1975	2462	224	-500	No Log Signature		5197
1582137.18	10389861.96	4237131219		H&GNRR	10	96	1980fswl&1980fsel	LAWRENCE (C.F.) & ASSOCIATES	1	Lacos State	3/17/1975	2416	390	-179	386	56	3598
1544568.69	10376607.67	4237131078		H&GNRR	10	57	660fnel&660fsel	TEXAS OIL & GAS	1	Crockett-State	10/5/1974	2504	769	504	764	654	6587
1764025.34	10328988.16	4237131032		H&GNRR	12	36	660fnwl&9900fswl	ESTORIL PRODUCING	1	Shell-Mann	7/17/1974	2235	1000	240	943	775	7851
1603466.10	10315321.96	4237130941	Wildcat D&A	T&StLRR	144	30	660fnl&660fel	DORCHESTER	1	Hinyard	3/1/1974	2814	1149	634	874	789	5945

Appendix B Table 1

Contact Elevations for Upper, Lower, and Porosity Zones for the San Andres

Research Partnership to Secure Energy for America

EASTING	NORTHING	API NUMBER	FIELD	SUR/TWP	BLK/RNG	SECTION	SPOT LOCATION	OPERATOR	WELL	LEASE NAME	COMPLETION DATE	DTM ELEVATION	Psa	Pgl/Pco	ϕ (Top)	ϕ (Base)	TD
1600037.69	10374307.40	4237130836	Brooklaw	H&GNRR	10	137	660fnwl&1980fswl	WELLAW CORPORATION	1	Moore Estate	8/21/1973	2402	567	-3	562	302	2740
1639933.71	10313917.61	4237130773	Chenot (WC)	H&GNRR	11	56	467fsl&2173fel	TEXAS OIL & GAS	2	Forest 56	2/18/1973	2979	949	439	757	669	5200
1603972.48	10358433.61	4237130771	Owego	H&GNRR	11	115	467fwl&2181fsl	LAWRENCE (C.F.)	1	ARCO R	3/31/1973	2435	850	95	825	440	2690
1535176.80	10375236.65	4237130731	Pecos Valley	Ashmore (M.J.)		4	467fnl&2157fel	EL CINCO PRODUCTION	1	Johnson Unit	4/3/1973	2522	497	-268	477	434	6077
1598389.61	10377967.32	4237130703	Brooklaw	H&GNRR	10	126	1980fnwl&1980fnel	WELLAW CORPORATION	1	Houston-State	8/8/1972	2428	598	-22	598	248	3515
1638045.60	10315044.51	4237130661	Chenot (WC)	H&GNRR	11	56	467fwl&1280fsl	TEXAS OIL & GAS	1	Forest 56	5/28/1972	2980	955	418	728	675	5271
1836948.51	10211565.25	4237130643	Wildcat D&A	I&GNRR	1	34	660fnl&3612fwl	FASKEN (David)	1	Smith (Ethel K.)	3/8/1972	2182	600	5	No Log Signature		8560
1551927.86	10422506.04	4237130374		H&GNRR	10	37	1980fnwl&1980fswl	LARIO OIL & GAS	1	Shearer	9/23/1970	2405	85	-580	No Log Signature		6900
1619764.35	10320225.44	4237130234	Chenot	T&StLRR	144	36	467fnl&467fel	REDFERN DEVELOPMENT-TEXAS OIL & GAS	1	Woodward 36	2/4/1970	2651	-117	-534	-268	-485	5039
1586871.61	10429574.70	4237130107		H&GNRR	9	30	660fwl&	BARNES (J.C.)	1	State-Brewer	7/23/1969	2367	-13	-681	-33	-313	3167
1580542.51	10410568.94	4237111243	Wildcat D&A	H&TCRR	2	21	467fsel&467fswl	ABELL (G.T)	1	Maxwell	8/26/1968	2384	-21	-702	-91	-396	5582
1697213.59	10282694.60	4237110734	Wildcat D&A	UL	17	10	467fel&2301fsl	MCFARLAND (B.L.)	1	University 10	7/10/1966	2787	851	-403	No Log Signature		9800
1584571.97	10407161.14	4237110732	Wildcat D&A	H&TCRR	2	25	660fsel&660fswl	ABELL (G.T)	1	Motley	6/22/1966	2381	59	-589	39	-307	5133
1637355.34	10239577.58	4237110638	Puckett North	EL&RRRR	100	7	1320fnl&1420fwl	FOREST OIL	1	Harral (Hellon)	1/22/1966	3327	802	544	774	563	10525
1664916.96	10355314.03	4237110426	Brown & Thorp, East	H&GNRR	11	19	660fwl&7630fsl	BROWN & THORP	2	Girvin (Roy) 1-19	10/11/1965	2331	526	6	501	436	3180
1664534.80	10269346.71	4237110396	McKenzie Mesa	GC&SFRR	603	8	660fnl&990fel	GENERAL CRUDE	1	McKenzie (Laro B.) 8	5/11/1965	3224.5	194.5	-335.5	137	-297	10424
1665809.56	10355494.28	4237110395	Brown & Thorp, East	H&GNRR	11	19	900fel&8018fsl	BROWN & THORP	1	Girvin (Roy) 19	5/10/1965	2307.5	465.5	-42.5	427.5	262.5	3166
1663931.15	10356554.17	4237110299	Brown & Thorp, E D&A	H&GNRR	11	18	467fel&2500fnl	BROWN & THORP	1	Scott (J.W.) et al	7/25/1964	2304.4	424.4	-57.6	404.4	202.4	3250
1661689.01	10357580.79	4237110298		H&GNRR	11	17	467fel&5930fsl	BROWN & THORP	2	Atlantic Fee 17	1/21/1965	2302.5	462.5	-77.5	437.5	342.5	3200
1660706.12	10359828.61	4237110297	M & M EAST	H&GNRR	11	17	367fwl&7830fsl	BROWN & THORP	1	Atlantic Fee 17	11/15/1964	2302	451	-103	442	357	3170
1592440.00	10402540.87	4237110292	Wildcat D&A	H&TCRR	2	29	2310fswl&2310fsel	ABELL (G.T)	1	U.S.M.	2/1/1965	2375	113	-475	108	-177	3719
1568203.15	10436181.98	4237110291	Wildcat D&A	H&TCRR	3	12	840fel&2371fnl	ABELL (G.T.)	5	State-Heierman	11/24/1964	2397	-71	-718	-109	-373	5930
1577851.20	10432379.45	4237110282	Abell, East	H&GNRR	9	26	467fsl&660fel	SOCONY-MOBIL	6	State-Grove A/C 5	7/22/1964	2389	2	-691	-36	-381	6145
1564257.42	10353000.05	4237110257		T&StLRR	140	13	660fnl&1980fwl	MORRIS (Ray) EXPL.	2	Donahue 13	4/1/1964	2564	864	174	No Log Signature		4692
1537358.27	10391145.09	4237110218	Wildcat D&A	H&GNRR	10	51	467fnwl&467fswl	HAYNES (C.H.)	2	Boren A	7/12/1964	2495	325	-421	307	-135	5244
1593317.25	10286550.88	4237110213	Wildcat D&A	UL	21	1	660fwl&1980fsl	GULF OIL	1	State KQ	7/31/1964	2880	-138	-545	-168	-500	8546
1824486.82	10239319.66	4237110205	Wildcat D&A	I&GNRR	1	43	852fsl&4397fwl	GROVER, MCCURDY	1	Monroe 43	7/21/1964	2127	485	-158	No Porosity Zone		8480
1541570.84	10389620.05	4237110201	Mesa Vista	H&GNRR	10	51	660fsel&1980fswl	EL CINCO & UNOCAL	1	Boren (Blanche)	7/10/1964	2485	335	-351	315	-65	4967
1521757.00	10401198.96	4237110187	Wildcat D&A	H&GNRR	10	18	1980fnel&1980fsel	BRANDYWINE	1	Grant-State	6/22/1964	2508	173	-694	No Log Signature		6283
1582116.90	10425248.38	4237110182	Abell, SE (Silurian)	H&TCRR	2	18	1900fwl2002fswl	BOREN, MAJOR & GIEBEL	1	Hall (Ellis)	4/30/1964	2394	-28	-648	-58	-289	5132
1581481.36	10422158.27	4237110180		H&TCRR	2	19	660fnel&2008fsel	BOREN, MAJOR & GIEBEL	1	Cole (H.C.)	4/7/1964	2396	-17	-734	-124	-332	5322
1567168.26	10439721.66	4237110173	Abell D&A	H&GNRR	9	22	467fsl&881fwl	ABELL (G.T.)	1	State-Cummins	10/23/1964	2396	216	-614	-34	-384	5518
1565408.29	10411298.65	4237110172	Wildcat D&A	H&GNRR	10	88	1838fsel&2100fswl	ABELL (G.T.)	1	State-Copeland	9/2/1964	2406	1	-664	-14	-214	6004
1540712.84	10388580.03	4237110162	MESA VISTA	H&GNRR	10	51		HAYNES (C.A.)	1	Boren	7/23/1963	2496	374	-329	346	-54	5038
1758736.12	10258405.74	4237110154	Wildcat D&A	GC&SFRR	C4	6	660fnl&660fel	BRANDYWINE OIL	1	Owens (Claud)	2/8/1964	2884.5	204.5	-335.5	Zeri Porosity		9128
1626280.22	10389627.32	4237110153	Wildcat D&A	H&GNRR	11	91	467fswl&467fnwl	BROWN & THORP	1	Atlantic Fee 91	1/26/1964	2333	623	-295	611	478	3441
1538886.05	10390184.09	4237110151	Mesa Vista (Montoya)	H&GNRR	10	51	660fswl&2173fnwl	HAYNES (C.A.)	1	Boren A	2/2/1964	2491	286	-394	No Log Signature		5082
1615630.48	10424269.99	4237110141	Wildcat D&A	H&GNRR	9	41	572fwl&8428fsl	ABELL (G.T.)	1	Mobil Fee	11/7/1963	2341	78	-597	61	-39	3924
1694333.28	10337354.33	4237110121	Wildcat D&A	H&GNRR	12	9	660fsl&660fel	RAY (B.A.)	1	Price (Mary)	7/29/1963	2306	581	56	534	398	6350
1542066.43	10388667.06	4237110104	Mesa Vista (Sullivan)	H&GNRR	10	64	330fnwl&1650fswl	EL CINCO	1	Sullivan	1/4/1964	2481	371	-309	No Log Signature		4984
1683411.44	10329691.30	4237110057	Wildcat D&A	H&GNRR	12	44	660fnl&660fwl	DEVELOPMENT LTD.	1	Develop. Ltd.-Nevill A	2/12/1963	2352	646	177	637	497	5520
1564313.69	10431170.52	4237110029	Abell East (Glorieta)	H&TCRR	3	10	467fnwl&467fswl	GREAT WESTERN	1	Cotten (J.B.) A	7/19/1965	2397	27	-623	7	-295	6012
1649424.33	10360818.57	4237110028	Brown & Thorp, West	H&GNRR	11	12	330(467)fel&5204(5013)fsl	BROWN & THORP	1	State	3/1/1964	2331.7	526.7	-18.3	446.7	279.7	3165
1500932.94	10417534.90	4237110018	Santa Rosa D&A	H&GNRR	8	107	660fsl&1980fwl	WILLIAMSON & U.S. SMELT.	1	Cadwell A 1 (Caldwell)	7/24/1963	2483	-97	-1037	No Log Signature		10001
1648685.01	10361807.22	4237110012	Brown & Thorp, West	H&GNRR	11	12	1156fel&6040fsl	BROWN & THORP	3	Roosevelt (Elizabeth)	2/18/1964	2330	534	-45	493	255	3161
1517621.88	10386248.09	4237106796	Wildcat D&A	H&GNRR	10	28	330fnel&990fsel	DAVIS (W.K.)	1	Robertson A	9/2/1957	2557	300	-540	237	-93	7477
1580213.55	10405984.66	4237106639	Wildcat D&A	H&TCRR	2	24	1980fnwl&1980fswl	NORSWORTHY (C.L., Jr.)	1	Fitting Estate	3/22/1962	2381	51	-759	41	-384	5258
1525608.49	10363958.61	4237106466	Wildcat D&A	GC&SFRR	105	13	660fsl&660fel	O'NEILL (Joseph I., Jr.)	1	Brownell-McGrew, et al	2/12/1954	2583	655	-17	No Log Signature		6065
1591326.96	10382034.96	4237105996		H&GNRR	10	112	660fsel&1980fswl	RODMAN-NOEL OIL	1	Barnes	10/27/1962	2356	381	-176	376	86	4396
1557784.70	10428634.79	4237105832	Abell East (Waddell)	H&TCRR	3	14	330fnel&2310fnwl	ABELL (G.T.)	7	State-Corrigan A	6/15/1961	2407	-5	-878	-13	-533	6072
1681617.47	10264035.29	4237105153	Wildcat D&A	GC&SFRR (Cooper)	604	15	660fnl&660fwl	TIDEWATER OIL	1	Carter (Mary McKenzie)	11/29/1961	3222	-30	-198	-48	-186	11063
1712158.83	10302138.00	4237104785		GC&SFRR	194	87	660fnl&610fel	TIDEWATER OIL	1	White & Baker Ranch B	6/29/1957	3078	678	118	673	323	9587
1646728.59	10336481.84	4237104729	WENTZ	H&GNRR	11	52	660fel&2310fnl	SUPERIOR OIL	1	Wangerin (Maude B.) 52	2/19/1954	2488	863	338	846	578	4477
1655578.74	10364042.18	4237104667	BROWN & THORP	H&GNRR	11	14				J. W. SCOTT STATE NO. 11		2299	454	-66	No Log Signature		
1654384.52	10359593.08	4237104661	BROWN & THORP	H&GNRR	11	14				J. W. SCOTT STATE #5		2309	457	-76	No Log Signature		
1654746.18	10361618.57	4237104658	BROWN & THORP NORTH	H&GNRR	11	14				J.W. SCOTT-STATE #2		2312	407	-88	No Log Signature		
1651497.42	10354075.86	4237104657	BROWN & THORP	H&GNRR	11	14				SCOTT STATE WSW #1		2350	463	-40	450	260	
1751334.48	10273026.37	4237104429	Sheffield, NW	TCRR	Z	4	1980fnl&1980fwl	STANDARD OF TX.	1	Perry (Frank A.) 24	5/26/1957	2631	476	-164	389	341	9757
1533141.58	10388046.86	4237104362	Wildcat D&A	H&GNRR	10	53	660fswl&790fsel	SOUTHERN CALIFORNIA PETROLEUM	1	Iowa Realty Trust	2/1/1957	2499	319	-449	289	-119	5479
1522463.39	10414520.31	4237104226	PECOS VALLEY	H&GNRR	10	21				REALTY TRUCK #1		2448	148	-549	96	-222	
1568547.76	10434435.79	4237104221	Abell	H&TCRR	3	12	330fel&330fswl	SINCLAIR OIL & GAS	1	Heirman (Bessie E.)	11/1/1955	2395	-53	-805			5953
1634211.22	10257686.64	4237104135	Hokit, North (Ellenburger) D&A	TCRR	180.5	3	660fel&1100fsl	SANDS (C.H.)	1	Nutt (Leroy)	5/2/1962	2960	155	-50	133	-35	10743
1741516.32	10255023.28	4237103547	Wildcat D&A	CG&SFRR	C4	15	800fsl&1920fel	WORTH EXPLORATION	1	Perry (Frank, Jr.)	3/18/1962	3022	75	-498	-26	-48	10817
1534863.73	10379667.25	4237103428	PECOS VALLEY SOUTH	H&GNRR	10	56	660fnwl&660fswl	WACKER (C.H.)	1	Breen (J.W.)	9/8/1958	2513	431	-387	343	-67	5575
1534701.87	10381566.17	4237103427	Pecos Valley (Devonian)	H&GNRR	10	55	660fsel&1980fswl	WACKER (C.H.)	1	Sanford-Gray	5/5/1957	2513	353	-420	293	-107	8095
1542298.96	10359969.64	4237103342	Wildcat D&A	T&StLRR	140	29	330fsl&990fwl	U.S. SMELTING & REFINING	1	State National Bank of El Paso	2/22/1957	2558	640	-122	458	130	6632
1550878.92	10371648.02	4237103300	APCO-Warner D&A	H&GNRR	10	59	330fnel&1980fnwl	U.S. SMELTING	1	Smith (Myron A.)	4/22/1962	2509	634	-26	583		5065
1530461.37	10409551.84	4237103299	Wildcat D&A	H&GNRR	10	22	660fnel&660fsel	U.S. SMELTING	1	Pecos Valley Oil A	6/25/1962	2455	93	-617	45	-405	6014
1552492.39	10371562.56	4237103291	APCO-Warner	H&GNRR	10	60	660fswl&1980fsel	U.S. SMELTING & REFINING	1	Knight-State	3/19/1962	2500	612	-29	561		5200

Appendix B Table 1
Contact Elevations for Upper, Lower, and Porosity Zones for the San Andres
Research Partnership to Secure Energy for America

EASTING	NORTHING	API NUMBER	FIELD	SUR/TWP	BLK/RNG	SECTION	SPOT LOCATION	OPERATOR	WELL	LEASE NAME	COMPLETION DATE	DTM ELEVATION	Psa	Pgl/Pco	ϕ (Top)	ϕ (Base)	TD
1636793.55	10328400.15	4237103172		H&GNRR	11	62		TEXAS OIL & GAS	3	Girvin (Roy) 62		2588	958	323	938	488	
1636040.59	10335631.54	4237103170	GIRVINTEX	H&GNRR	11	72	467fsl&467fel	INTEX OIL	1	Girvin (Roy) 72	3/17/1953	2512	872	162	857	490	3033
1635368.52	10328780.01	4237103169	Wildcat D&A	H&GNRR	11	62	467fsl&467fwl	INTEX OIL	1	Girvin (R.) 62	9/29/1954	2572	922	292	892	564	4650
1822843.87	10259004.86	4237103144	Millard Queen	I&GNRR	1	49	660fnl&7744fwl	HUMBLE OIL	8	Holmes (Millard)	5/15/1958	2171	586	1	364	331	8290
1518289.11	10397187.24	4237103086		H&GNRR	10	15	1980fsel&1980fnel	HUMBLE OIL	1	Unsicker (Alma B.)	8/19/1948	2514	151	-676	98		8460
1646680.21	10261159.02	4237103063	Hokit Ellenburger D&A	Simmons (Mary)	206	1	660fsl&3970fel	HUMBLE OIL	1	Talbert (Earl L.)	8/31/1961	3289	49	-226	19	-206	8942
1649600.43	10176561.66	4237103037	Wildcat D&A	T&StLRR	129	1	660fnl&660fel	HUMBLE OIL	1	Edwards (W.M.)	7/29/1957	3211	1441	966	1311	1073	17880
1597593.68	10371060.54	4237102999	Wildcat D&A	H&GNRR	10	138	660fnwl&1980fnel	HUMBLE OIL	1	Barnes (O.L.)-State B		2420	645	70	590	220	4155
1521307.27	10342339.25	4237102967	Wildcat D&A	Kelly (Downs)		211	660fsl&660fwl	HUMBLE OIL	2	San Pedro Ranch	10/3/1958	2705	-443	-785	-526	-634	9393
1533509.92	10352590.64	4237102966	Wildcat D&A	Duval (J.C.)		2	660fsl&660fel	HUMBLE OIL	1	San Pedro Ranch	8/27/1949	2609	1024	199	739	704	5656
1596079.51	10292846.72	4237102938	HINYARD	T&StLRR	144	7	2080fnl&2080fel	HUMBLE OIL	1	Hinyard (Paul)	12/5/1962	2935	300	5	5	5	8270
1624574.13	10240581.32	4237102823	Puckett, North (Ellenburger)	EL&RRRR	100	10	660fnl&660fel	HUNT (Hassie)	4	Wimberly (H.A.)	6/14/1962	3378	118	-189	85	-167	14875
1631551.66	10249621.76	4237102768	Puckett, North (Ellenburger)	EL&RRRR	100	42	660fwl&1980fnl	HUNT (Hassie)	2	Wimberly (H.A.)	9/6/1961	3430	175	-620	89	-562	11720
1629843.10	10248315.70	4237102764	Puckett North (Ellenburger)	EL&RRRR	100	1	990fel&1980fsl	HUNT (Hassie)	2	Puckett (Dow)	10/18/1961	3343	365	-147	310	-110	10560
1619304.54	10257725.21	4237102762	Wildcat D&A	T&StLRR	125	13	660fsl&1218fel	HUNT (Hassie)	1	Nutt (J.L.) B	2/22/1961	3010	275	-75	237	-49.5	10200
1632519.17	10239047.14	4237102758	Puckett North (Ellenburger)	EL&RRRR	100	8	1980fnl&1980fwl	HUNT (Hassie)	1	Harral	10/25/1962	3313	328	95	303	112	10594
1594040.16	10399543.64	4237101603	Wildcat D&A	H&GNRR	10	118	660fwl&990fsl	DONNELL et al	1	Mueller (Leona)	8/2/1962	2364.5	154.5	-335.5	104.5	-135.5	3749
1560549.65	10428001.31	4237101407	Abell East (Clearfork)	H&TCRR	3	13	330fsel&1008fswl	BURK ROYALTY	1	Eaton	9/9/1959	2405	-89	-674			6040
1643924.97	10366097.67	4237101270	WENTZ	H&GNRR	11	10		BROWN & THORP	1	Hart (E.N.)	6/1/1961	2311.4	617.4	-88.6	561.4	209.4	3185
1731861.71	10315424.76	4237101078	Wildcat D&A	GC&SFRR	194	51	1980fsl&1980fel	BELL & DANSFIELD	1	Lowery & Wilson	5/1/1961	2435	582	-7	435	410	7350
1544309.06	10430109.90	4237101077	Wildcat D&A	H&GNRR	9	14	660fel&1980fsl	BELL & DANSFIELL & NORTH CENTRAL	1	Borgens (Lillian)	7/22/1961	2415	219	-687	No Log Signature		5450
1579367.94	10418200.08	4237101076	Wildcat D&A	H&TCRR	2	19	330fswl&990fsel	BELL & DANSFIELL	1	Kistler (H.L.)	12/29/1961	2392	-54	-723	-88	-398	5625
1699343.65	10343608.35	4237100539	El Cinco Devonian	H&GNRR	12	11	330fwl&8550fsl	EL CINCO PRODUCTION	1	Price (Ruth Mary) B	11/15/1961	2278	508	-62	495	428	5400
1652908.95	10316036.45	4237100413	Putnam Wolfcamp	H&GNRR	11	123	615fel&660fsl	CHAMPLIN OIL	1	Cities Service et al	8/16/1960	2660	1068	420	1045	660	5047
1657458.74	10361681.43	4237100353	Wildcat D&A	H&GNRR	11	15	660fel&8502fsl	ATLANTIC REFINING	1	Cardova L	12/24/1958	2302	452	-38	442	337	5290
1560933.06	10438285.14	4237100097	DAMERON	H&TCRR	3	18	2500fel&4600fnl	ABELL (G.T.)	3	Sidlo	12/12/1961	2401	-104	-781	-109	-397	3478
1595129.13	10410886.40	4237100091	Wildcat D&A	H&TCRR	2	27	330fnel&330fsel	ABELL (G.T)	1	Williams 27	4/10/1965	2367	95	-578	22	-183	3720
1583366.94	10427372.73	4237100082	Abell, Silurian	H&GNRR	9	29	330fwl&990fsl	ABELL (G.T.)	1	W.O.R.	12/2/1950	2387	-73	-813	-111	-339	5604
1573003.93	10447650.55	4237100076	Wildcat D&A	H&GNRR	9	23	330fel&9407fsl	ABELL (G.T.)	1	Patterson	9/13/1962	2382	207	-451	-58	-372	4038
1584986.21	10435630.46	4237100056	Abell, Silurian	H&GNRR	9	29	330fwl&9406fsl	ABELL (G.T.)	4	Piper (R.G.)	1/15/1951	2372	-123	-720	-128	-408	6215
1583904.40	10438337.46	4237100054	ABELL	H&GNRR	9	28		ABELL (G.T.)	1	State River Bed A	2/20/1952	2367	155	-651	-183	-418	5083
1583904.40	10438337.46	4237100053	Abell Clearfork	H&GNRR	9	20	990fsel&5855fswl	ABELL (G.T.)	2	State-Neely	6/29/1962	2385	272	-721	32	-308	4020
1558448.74	10424436.96	4237100049	Abell East (McKee & Waddell)	H&TCRR	3	8	330fnwl&2117fswl	ABELL (G.T.)	1	State-Hart	9/15/1960	2406	-14	-724	-52	-268	6075
1555094.16	10425574.31	4237100040	Abell Grayburg	H&TCRR	3	14	990fswl&2310fnwl	ABELL (G.T.)	2	State-Corrigan B	10/20/1960	2403	59	-599	51	-282	3496
1559343.23	10426673.54	4237100038	Abell East (Waddell)	H&TCRR	3	14	440fsel&799fnel?	ABELL (G.T.)	6	State-Corrigan A	1/10/1960	2403	-9	-692	-63	-317	6090
1558411.44	10425918.43	4237100035	Abell East (Waddell)	H&TCRR	3	14	660fsel&1980fnel	ABELL (G.T.)	3	State-Corrigan A	12/3/1959	2406	1	-724	-64	-444	6511
1556585.65	10425015.01	4237100034	Abell East (Waddell)	H&TCRR	3	14	1460fswl&1460fsel	ABELL (G.T.)	2	State-Corrigan A	10/4/1957	2402	54	-653	No Log Signature		6102
1568975.95	10445031.64	4237100033	Abell, NW	H&GNRR	9	22	1048fwl&6142fsl	ABELL (G.T.)	2	Sharp (Bessie)	3/20/1951	2380	204	-784	200	-120	5525
1564528.86	10453532.62	4237100014	Wildcat D&A	H&GNRR	9	20	1014fwl&5805fsl	ABELL (G.T.)	3	Denton (Harry)- State	11/27/1962	2386	215	-756	-84	-366	1730
1567446.68	10411284.94	4237100010	Wildcat D&A	H&GNRR	10	88	330fsel&1980fnel	ABELL (G.T.)	1	Cox	11/26/1962	2400	-6	-638	-15	-290	5979
1584466.22	10433127.27	4237100009	Abell, Perm	H&GNRR	9	29	330fwl&	ABELL (G.T.)	1	Byerley (L.G.)	4/2/1950	2372	-176	-756	-178	-348	5814
1592369.19	10391781.48	4237100004		H&GNRR	10	114	660fnel&660fsel	ABELL (G.T.)	1	State-Barnes et al	11/10/1954	2391	341	-284	336	101	4471
1427125.00	10775226.09	3002525744	LANGLIE-MATTIX	S 24	E 37	22	1980 fsl 660 fel	AMOCO PROD CO	7	Myers A Federal	1/30/1978	3235	-450	-1555	-715	-1110	3570
1400305.77	10896083.90	3002523178		S 20	E 37	34	1980 fnl & wls	PAN AMERICAN PET CORP	14-B	14 GILLULLY - FEDE	8/1/1969	3515	-496	-1718	-890	-1110	8019
1401855.55	10905242.84	3002522611	CASS	S 20	E 37	22				12 GILLULY - FEDER		3529	-441	-1646	-621	-971	
1447209.42	10838293.08	3002521050	DRINKARD	S 22	E 38	20	1980 fsl & fwl s	TEXACO INC	22	AH Blinebry- Fed NCT 1-22	2/27/1965	3401	-709	-1864	-954	-1219	7150
1386179.97	10965348.94	3002520651	GOODWIN	S 18	E 37	30	1980 fnl & 1980 fwl	CONOCO INC	2	GOODWIN 2	9/29/1980	3762	-753				7600
1238220.48	11007955.04	3002520568	MALJAMAR	S 17	E 32	21	660fsl&fwl	BUFFALO	12	Baish A	8/7/1940	4002	197				4018
1397067.08	10912041.25	3002520535	MONUMENT	S 20	E 37	16	1980 fnl & 1650 fel	MARATHON OIL CO	6	State Hansen	8/2/1963	3552	-366	-1526	-748	-1278	6650
1315796.32	10994862.01	3002520510	VACUUM	S 17	E 34	35				STATE H-35 8		4018	-372	-1847	-677	-1122	
1327046.44	10979025.76	3002520378	VACUUM SOUTH	S 18	E 35	17	510 fnl & wl	SINCLAIR O & G	4	State -Lea 403	4/21/1968	3959	-1037		-1366	-1634	11896
1316825.54	10996219.84	3002520116	VACUUM	S 17	E 34	25	660 fsl 560 fwl	MARATHON OIL CO	5	State-McCallister	5/1/1963	4019	-343	-1803	No Log Signature		12195
1437869.65	10744325.81	3002512416	JUSTIS	S 25	E 38	19	2310 fnl 330 fwl	TEXACO		CE PENNY NCT-4 4		3078	-576	-1662	-622	-1187	
1443960.99	10815929.95	3002512203		S 23	E 38	7	850 fsl 660 fel	MURPHY H BAXTER	1	Gibson-Fed 1	10/7/1959	3389	-1191		-1256	-1321	9921
1419073.15	10767481.52	3002512189	DRINKARD	S 22	E 38	32				STATE S 1		3259	-771	-1941	-1003	-1231	
1444239.79	10827789.01	3002512177	DRINKARD	S 22	E 38	31	660 fsl & fel	TEXACO INC	1	AH Blinebry- Fed NCT	6/15/1959	3322	-560	-1753	-693	-1086	7105
1446975.69	10840956.03	3002512143	DRINKARD	S 22	E 38	20	660 fnl 1650 fwl	TEXACO INC	1	WM L Nix	4/11/1959	3380	-710	-1925	-800	-1707	7250
1444573.24	10840480.48	3002512139	DRINKARD	S 22	E 38	19	660 fnl & 660 fel	TEXACO EXPL & PROD	9	AH Blinebry Fed NCT 19	3/11/1997	3386	-606	-1824	-832	-1574	7200
1446023.80	10842304.55	3002512118	DRINKARD	S 22	E 38	17	660 fsl & wls	THE TEXAS CO	1	Dolly Ballinger	2/25/1959	3378	-702	-1932	-832	-1607	7200
1422090.01	10730488.95	3002511933	CROSBY	S 26	E 37	3	660 fn&wls	AMERADA PET. CORP	3	CC Cagle C3	1/24/1962	2994.15	-1030.85	-2218.85	-1555.85	-1895.85	8824
1431873.42	10740763.60	3002511793	JUSTIS	S 25	E 37	26	660 fnl 330 fel	AMERADA HESS CORP	10	Ida Wimberly	12/4/1981	3044	-568	-1686	-586	-1176	5949
1435101.03	10738400.77	3002511756	JUSTIS	S 25	E 37	25	2310 fsl 2309.4 fwl	ATLANTIC REFINING		CARLSON-FED A 1		3074	-456	-1546		-1011	
1435592.51	10746038.63	3002511729		S 25	E 37	24	660 fnl 1980 fel	GETTY OIL CO	6	Coates	8/18/1967	3084	-463	-1541	-486	-1121	8177
1431903.47	10742083.97	3002511701	JUSTIS	S 25	E 37	23	660 fsl 330 fel	ANDERSON -PRICHARD OIL CORP	1	Carlson B	10/19/1959	3044	-598	-1796	-776	-1131	5965
1432805.46	10750996.29	3002511558	JUSTIS	S 25	E 37	13	990 fnl 890 fwl	ANDERSON PRICHARD OIL CORP	6	Blocker- Federal	6/9/1960	3114	-491	-1580	-586	-1211	5992
1434415.69	10749631.14	3002511556	JUSTIS	S 25	E 37	13	2310 fnl 1980 fwl	ANDERSON PRICHARD OIL CORP	4	Blocker- Federal	11/13/1958	3095	-490	-1567	-705	-1165	7020
1432041.95	10761901.33	3002511398	JUSTIS NORTH	S 25	E 37	2	663 fnl 660 fel	AMERADA PETROLEUM		STATE NJA 1		3174	-431	-1486	-526	-1145	
1432992.68	10760556.30	3002511389	WILDCAT	S 25	E 37	1	1980 fnl 330 fwl	J C WILLIAMSON	4	Westates Federal	6/6/1961	3138	-482	-1542	-652	-1162	8700
1425932.64	10780570.17	3002511111	FOWLER	S 24	E 37	15	1980 sl & els	STANOLIND	1	SOUTH MATTIX UNIT 1	5/20/1947	3257	-633	-1547	-633	-1093	9705

Appendix B Table 1

Contact Elevations for Upper, Lower, and Porosity Zones for the San Andres

Research Partnership to Secure Energy for America

EASTING	NORTHING	API NUMBER	FIELD	SUR/TWP	BLK/RNG	SECTION	SPOT LOCATION	OPERATOR	WELL	LEASE NAME	COMPLETION DATE	DTM ELEVATION	Psa	Pgl/Pco	ϕ (Top)	ϕ (Base)	TD
1434224.38	10833655.42	3002510462	BLINEBRY	S 22	E 37	26	2310 fsl 330 fel	RESLER & SHELDON	1	Allie Lee	12/13/1957	3322	-602	-1768	-788	-1373	7520
1423732.43	10849441.57	3002510126	PADDOCK	S 22	E 37	9	1980 fsl & 660 fel	HUMBLE OIL	5	Greenwood	5/12/1949	3415	-563		-765	-855	3725
1423698.85	10848121.07	3002510122	DRINKARD	S 22	E 37	9	660 fsl & fel	HUMBLE OIL		GREENWOOD 1	11/23/1948	3429	-456	-1649	-556	-1361	6545
1415829.74	10851834.76	3002510117	DRINKARD	S 22	E 37	8	660 fnl & 1980 fwl	CHEVERON USA INC	1	Falby CP A Fed	11/5/2003	3436	-569	-1644	-579	-879	6570
1414473.97	10849783.78	3002510106	PENROSE-SKELLY	S 22	E 37	8				CP FALBY-FEDERAL B 4		3423	-542	-1667	-597	-917	
1391818.37	10785403.37	3002509535	JALMAT	S 24	E 36	10	660 fsl & 660 fwl	JOESPH I O'NEIL JR	2	Rocket	7/9/1958	3389	-964				3592
1448252.51	10963709.88	3002507953	HOBBS EAST	S 18	E 39	30				SAMUEL E CAIN 4		3628	-852				
1449412.03	10962312.23	3002507951	HOBBS EAST	S 18	E 39	30				SAMUEL E CAIN 2		3617	-833				
1435509.24	10941739.77	3002507698	HOBBS	S 19	E 38	15				FRANK SELMAN 2		3604	-578				
1435725.15	10950814.17	3002507595	HOBBS	S 19	E 38	3	760 fsl 990 fel	STANOLINDS O & G	27	WS Capps	7/20/1955	3615	-585				4280
1425503.05	10966527.89	3002507373	HOBBS	S 18	E 38	20	330 fsl & 990 fel	HUMBLE O & G	3	Bowers B	1/22/1933	3643	-457				4225
1443714.39	10981291.39	3002507331		S 18	E 38	12	330 fnl & 990 fwl	ROBERT N ENFIELD	1	Sinclair Williams	1/18/1961	3674	-1218	-2601	-1551	-2164	6500
1441845.39	10983311.43	3002507316		S 18	E 38	2	1650 fsl 990 fel	BISHOP CANYON URANIUM CORP	1	B Keohane	3/7/1959	3667	-1109	-2553	-1635	-1748	5296
1445029.10	10983810.90	3002507315		S 18	E 38	1	2221 fsl 2175 fwl SEC	BISHOP CANYON URANIUM	1	Tomlinson	12/11/1957	3685	-1283				5260
1413549.47	10866417.60	3002506909	DRINKARD	S 21	E 37	30				VM HENDERSON 3		3482	-378	-1718	-548	-1388	
1433555.93	10876465.11	3002506582	DRINKARD	S 21	E 37	14	1980 fnl &fel	SHELL OIL CO	1	JR Smith JR	5/20/1952	3430	-530	-1792	-600	-1585	7573
1396378.96	10910723.24	3002506116	MONUMENT	S 20	E 37	16	1980 fsl & 2310 fel	AMERADA HESS CORP	1	State Q	8/21/1973	3546	-326	-1562	-754	-1514	6938
1418720.33	11203914.20	3002505008		S 11	E 37	9	1787 fsl 2171 fwl	RUDMAN & DORFMAN PROD	1	E. Fife	2/15/1960	3966	-322	-1499	-1084	-1229	12722
1391532.41	10888509.31	3002504480	OIL CENTER	S 21	E 36	4	3300 fsl 2310 fel	CONOCO INC	19 B-4	Meyers B-4 19	3/31/1981	3585	-885	-1655	-965	-1135	12010
1376972.93	10913808.78	3002504270	WILDCAT	S 20	E 36	14	810 fnl & 660 fel	CONTINENENTAL O & G	10	Sanderson A 14 NO 10	11/24/1959	3569	-411	-1631	-1164	-1222	9444
1394062.64	11070052.72	3002503696	Dean (Penn) D&A	S 15	E 36	23	660fnl&1980fwl	TRICE PRODUCTION	1	Robinson (Sue Alva)	1/27/1960	3886	-984	-2544	No Porosity Zone		12025
1327068.16	10974906.99	3002503121		S 18	E 35	17	660 fsl & 660 fwl	SINCLAIR O & G	1	State Lea 401	6/4/1956	3958	-942				5305
1332604.28	10987902.47	3002503044	VACUUM	S 18	E 35	4	1980 fnl 660 fwl	STANDARD OIL CO OF TEXAS	2	Vac Edge Unit	10/17/1960	3961	-814	-2119	-829	-1399	8984
1339292.17	10992648.43	3002503024	VACUUM	S 17	E 35	34				STATE M 9		3942	-541	-1838	-558	-1048	
1342309.12	11003546.17	3002502856		S 17	E 35	22				STATE AC 1		3942	-628	-2178	-1408	-1573	
1234362.80	11011057.27	3002502028	MALJAMAR	S 17	E 32	17	330 fsl & 1980 fsl	BUFFALO OIL	19	Mitchell B	8/25/1950	4020.5	170.5	-1297.5	-99.5	-777.5	5386
1261215.41	10935636.67	3002501699		S 19	E 33	30	1980 fsl 660 fel	SINCLAIR O & G	2	FEDERAL CARDER #2	3/29/1956	3585	-1302	-2813	-1626	-2195	5600
1260728.41	10996533.71	3002501339	CORBIN	S 17	E 33	31	710fnl&2310fwl	CARPER DRILLING	1A	Federal MA	12/26/1959	4009.5	-440.5	-2205.5	-895.5	-1490.5	10015
1242105.52	10997543.76	3002500815	Maljamar	S 17	E 32	33	660fnl&1980fwl	COCKBURN	4	Pearsall-Federal A	3/27/1941	3951	-59				3955
1250264.42	10999528.95	3002500713		S 17	E 32	26				USA-MILLER 1		3969	-231	-1931	-541	-1021	
945745.19	10860890.84	3001520138	ROCKY ARROYA	16	S 22	E 22	1800 FNL 1980FWL	CARL A. SCHELLINGER	1	MAHUN STATE	1977	4360	4245	2770	No Log Signature		7610
998752.97	10937007.68	3001510477	DAGGER DRAW	1	S 20	E 24	660 FNL 660 FWL	YATES PETROLEUM	1	LOYD FOSTER AN	1968	3635	3105	1535	2485		8240
1051587.66	10984135.61	3001510431	ATOKA	16	S 18	E 26	990 FSL & 990 FEL		1	MARATHON-STATE AM		3370	2585	1108	No Log Signature	1700	
1199679.23	11006195.19	3001505265	CEDAR LAKE	19	S 17	E 31	1650 FSL 990 FEL	FERN OIL	19	FRIESS-FEDERAL	1962	3620	443	-1000	170	-780	7100
1193540.01	11006156.09	3001504319	JACKSON	24	S 17	E 30	1420 FSL 1980 FEL	BURNETT OIL	23	JACKSON B	1995	3676	465	-1098	6	-374	7028
1174078.85	11006960.98	3001504222	LOCO HILLS	20	S 17	E 30	1650 FSL 410 FEL	FRANKLIN, ASTON & FAIR	4	MCINTYRE-FEDERAL A	1961	3644	724	-731	344	192	6857
1135863.44	10937325.88	3001503612	BURTON NORTH	32	S 19	E 29	660 FNL 660 FWL	SUNRAY MID-CONTINENT	1	NEW MEXICO STATE Q	1960	3308	658		598	423	12429
1143373.84	11003001.24	3001503172		28	S 17	E 29	1980 FSL 660 FWL	GULF OIL	1	EDDY-STATE DF	1960	3583	1113	-317	883	180	6273
1163247.07	11005359.18	3001503083		25	S 17	E 29	330 FNL 660 FSL	GENERAL AMERICAN OIL	5	GRAYBURG DEEP UNIT	1960	3618	872	-560	608	-172	7225
1114367.60	10996384.19	3001502588	EMPIRE	4	S 18	E 28	330 FNL 2272 FEL	PAN AMERICAN	1	STATE BL	1960	3670	1450	-10	1155	518	6334
1111911.72	10996094.09	3001502587	EMPIRE	4	S 18	E 28	663 FNL 550FWL	PAN AMERICAN	1	STATE BC	1960	3673	1539	118	1183	659	6367
1116389.53	11002283.54	3001501595	EMPIRE	28	S 17	E 28	330 FSL 330 FEL	DELHI-TAYLOR OIL	14	STATE	1960	3690	1664	200	1323	816	6866
1071948.52	10981823.37	3001500924		19	S 18	E 27	660 FNL 1980 FEL	HUMBLE	1	KATHLEEN STECKEL ET AL	1960	3303	2039	511	1705	1103	9784
1077391.37	10985558.62	3001500914	RED LAKE	17	S 18	E 27	2310 FSL 1650 FEL	HUMBLE	24	ABO CHLK BLFF DRW UN	1961	3448	2030	408	1698	1086	5600
1081289.33	10986556.16	3001500900	EMPIRE	16	S 18	E 27	1980 FSL 660 FWL	HUMBLE	16	ABO CHLK BLFF DRW UN	1960	3459	1994	421	1466	1095	5797
1093368.54	10988824.03	3001500870	WILDCAT	11	S 18	E 27	1980 FSL & 1980 FEL		1	RUTH C. MCPHERSON		3593	1659	36	1156	753	
1092233.83	10991468.02	3001500864	WILDCAT	11	S 18	E 27	660 FNL 1980 FWL	PAN AMERICAN	1	USA MALCO REFINERIES A	1957	3584.6	1622.6	205.6	1161.6	814.6	6315
1087901.41	10990688.55	3001500856	EMPIRE	10	S 18	E 27	1650 FNL 2310 FEL	PAN AMERICAN	5	MALCO REFINING-FED D	1960	3485	1803	235	1255	922	6172
1087385.82	10996468.50	3001500752	EMPIRE	3	S 18	E 27	957 FNL 23-9' FWL	PAN AMERICAN	9	MALCO REFINING-FED H	1959	3606	2016	626	1721	1231	5711
1092154.65	10994111.27	3001500735	EMPIRE	2	S 18	E 27	1980 FSL 1830 FWL	AMOCO	1	STATE AU	1973	3541	1837	411	1498	981	6676
1064804.97	10971842.25	3001500273	DAYTON	36	S 18	E 26	330 FNL 1980 FWL	E. P CAMPBELL	1	B AND B-FEDERAL	1959	3290	2070	490	1730	1240	6389
1050263.90	10971964.70	3001500259	DAYTON WEST	33	S 18	E 26	660 FNL 1980 FEL	E. P. CAMPBELL	1	CLEVELAND	1959	3387	2397	907	2102	1522	6100
1042656.89	10971922.20	3001500258	ATOKA	32	S 18	E 26	990 FNL 990 FWL	YATES PETROLEUM	1	NIX + CURTIS 'J-F'	1978	3429	2555	1134	2057	Casing problem	9295
1055819.41	10977080.09	3001500251	ATOKA	27	S 18	E 26	660FNL 1980 FEL	YATES PETROLEUM	5	HAWKINS GY	1995	3328	2328	810	1998	1445	6262
1032881.88	10963373.45	3001500109		1	S 19	E 25	660FSL 1980FWL	PAN AMERICAN	1	BH MATLOCK	1959	3421	2541	981	1971		9400
1032207.17	11065166.93	3001500090	WILDCAT	2	S 16	E 25	330 FNL 2982 FWL	HUMBLE	1	PEARSON	1950	3450	2853	1742	2564	2216	8248
982234.43	10921696.76	3001500057		21	S 20	E 24	660 FNL 660 FWL	MONSANTO CHEMICAL	1	STANDARD MA	1960	3794	3382	1879	No Log Signature		5883
948824.44	10791880.12	3001500020	WILDCAT	22	S 24	E 22	2040 FNL 1980 FWL	HUMBLE	3	HUAPACHE	1959	5625.5	5213.5	3840.5	Casing Problem		5670
955916.13	10796853.63	3001500018		14	S 24	E 22	2042 FNL 1618 FNL	HUMBLE	5	HUAPACHE OIL UNIT	1960	5353.5	5223.5	3753.5	No Log Signature	Casing Problem	3505
933241.57	10840991.82	3001500012		6	S 23	E 22				HUAPACHE 1		5125	4995	3537	No Log Signature		
1398711.76	11266624.47	Not Available		S 09	E 36	8	660 fsl & 660 fwl	MAGNOLIA	1	Walker -Federal	1/15/1950	4100	24	-1400	-810	-900	9729
1388133.38	11266906.19	Not Available		S 09	E 35	12	660 fsl & 1980 fwl	MAGNOLIA PET. CO	A 2	Betenbough	4/29/1950	4129	19	-1311	-619	-751	9639
1433829.55	10942422.81	Not Available	HOBBS	S 19	E 38	15	1650 fnl & 990 fwl	PAN AMERICAN PET CORP	1	State A Tract 9-1 SWD	8/10/1957	3614	-526				4872
1421805.39	10834282.53	Not Available		S 22	E 37	28	330 fnl & 2310 fel	SINCLAIR OIL & GAS CO	3	Christmas	1/27/1957	3354	-546	-1714	-711	-1266	

Psa	Top of San Andres
Pgl/Pco	Top of Glorieta / Cutoff
ϕ (Top)	Top of Porosity Zone
ϕ (Base)	Base of Porosity Zone

APPENDIX C

Pre-Development Heads in The Artesia Fairway

Appendix C Table 1
Pre-Development Heads in the Artesia Fairway
Research Partnership to Secure Energy for America

ID	X Coordinate	Y Coordinate	Unit	Observed Head	Model Simulated Head	Residual
1	1216307.048	11032088.357	Grayburg and San Andres Limestone, Undivided	3500	3487	12.8
2	1241833.682	11008063.289	Grayburg and San Andres Limestone, Undivided	3395	3361	34.0
3	1262855.617	10940192.472	Seven Rivers Formation	3060	3255	-194.5
4	1272765.957	10959112.213	Queen Formation	3160	3238	-77.9
5	1293487.578	10941393.725	Queen Formation	3015	3155	-140.0
6	1317212.333	10929681.505	Yates Formation	3090	3073	17.4
7	1315110.139	10918870.224	Bone Spring Limestone	3060	3078	-17.8
8	1321116.406	10925477.118	Queen Formation	3090	3069	20.5
9	1334330.194	10989143.548	Glorieta Sandstone	3040	3007	33.0
10	1328924.554	10990044.488	Grayburg Formation	3025	3030	-4.9
11	1299493.845	11011366.736	Grayburg Formation and San Andres Limestone, Undivided	3160	3168	-8.5
12	1320275.529	11007762.975	Grayburg Formation and San Andres Limestone, Undivided	3050	3090	-39.9
13	1369226.605	11016772.376	San Andres Limestone	3110	2985	124.9
14	1385443.526	11026382.403	San Andres Limestone	3160	2970	190.2
15	1430490.528	10957910.959	Grayburg Formation and San Andres Limestone, Undivided	3095	2966	129.2
16	1446106.822	10947399.992	Yates Formation	3060	2961	98.8
17	1386344.466	10939591.845	Yeso Formation	3040	3012	28.2
18	1383041.019	10924275.864	Yeso Formation	3060	3027	32.5
19	1379227.040	10864723.727	Grayburg Formation and San Andres Limestone, Undivided	3090	3081	9.1
20	1381629.546	10856014.640	Seven Rivers Formation	3065	3083	-18.2
21	1399648.347	10861720.594	Grayburg Formation and San Andres Limestone, Undivided	3020	3069	-48.9
22	1414363.701	10904665.403	Grayburg Formation	3050	3028	21.9
23	1425775.609	10890250.362	Grayburg Formation	2985	3038	-53.3
24	1418267.775	10853522.039	Queen Formation	3020	3067	-46.9
25	1437788.143	10852020.472	Yeso Formation	2980	3065	-85.1
26	1442292.843	10834001.672	Yeso Formation	2980	3073	-93.5
27	1393642.080	10774479.566	Seven Rivers Formation	3070	3095	-25.3
28	1433884.069	10766671.419	Seven Rivers Formation	2910	3093	-183.2
29	1403552.421	10751355.438	Seven Rivers Formation	3100	3095	4.8
30	1451902.870	10681832.897	Glorieta Sandstone	3000	3107	-107.5
31	1419168.715	10640089.342	Seven Rivers Formation	3130	3122	8.3
32	1422772.475	10639789.028	Yates Formation	3130	3122	7.9
33	1438989.396	10624172.734	Yates Formation	3100	3129	-28.8
34	1448269.079	10567894.013	Yates Formation	3150	3148	2.2
35	1503827.048	10570897.146	Clear Fork Group	2970	3158	-187.8
36	1468390.073	10560386.179	Yates Formation	3080	3155	-74.7
37	1491994.702	10476178.316	Yates Formation	3200	3199	0.9
			Mean Error			-19.4
			Absolute Mean Error			60.6
			Root Mean Squared Error			84.5
			RMSE over range of heads			0.14

APPENDIX D
Pumping Records

RPSEA
ARCADIS

Appendix D Table 1
Estimated Annual Pumping Rates for the Lea County Water Flood Supply Wells
Research Partnership to Secure Energy for America

		Year	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	1986 - 2010
X	Y	Stress Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	1 - 25
Coordinate	Coordinate	Well	Pumping Rate (gpm)																									
1387319.85756	10886403.8972	CP670	362	362	362	362	362	362	362	362	362	362	261	246	202	55	99	13	45	4	3	0	0	0	0	0	0	4,551
1389740.60665	10889299.7466	CP694	0	107	107	107	107	107	107	107	107	107	284	58	71	0	178	176	168	251	11	77	147	156	140	114	54	2,851
1392636.45603	10886924.2451	CP697	0	0	530	530	530	530	530	530	530	530	477	466	376	504	319	413	449	462	314	145	55	86	37	21	7	8,369
1384650.24642	10885159.5869	CP693	0	0	644	644	644	644	644	644	644	644	526	295	66	0	0	0	0	0	0	0	0	0	0	0	0	6,037
1393134.18014	10881607.6467	CP695	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1388541.54402	10882399.4805	CP696	0	0	632	632	632	632	632	632	632	632	612	340	310	3	58	0	195	49	0	0	0	0	0	0	0	6,626
1402500.99730	10859595.3925	CP760	0	0	0	0	0	0	0	0	0	487	437	631	712	534	341	378	374	278	241	79	13	92	56	83	102	4,838
1404398.82115	10856221.4835	CP761	0	0	0	0	0	0	0	430	430	430	232	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1,521
		Total (gpm):	362	470	2,275	2,275	2,275	2,275	2,275	2,705	2,705	3,192	2,828	2,036	1,736	1,097	995	981	1,231	1,044	569	301	215	335	234	217	163	34,792
		Total (MG):	191	247	1,197	1,197	1,197	1,197	1,197	1,423	1,423	1,679	1,488	1,071	913	577	524	516	648	549	299	158	113	176	123	114	86	18,299

gpm = gallons per minute

MG = million gallons per year

Note: Pumping rates prior to 1995 were estimated based on the 1995 pumping rate data.

Source: New Mexico Office of the State Engineer WATERS Database (2011)

Appendix D Table 2
Summary of Pecos County Supply Wells
Research Partnership to Secure Energy for America

Well Name	Year	Depth (ft bgs)	Use	Rate (gpm)	Owner	X Coordinate	Y Coordinate	Date Measured	Used*	Ground Surface Simulated Head Elevation (ft amsl)
C-14	1926	2,126	Irrigation		Blackman	1537857.84400	10426565.8267		Yes	2,402
C-10	1946	2,661	None		Sun Ray Oil	1524930.84329	10421325.1507		No	
C-18		2,307	Irrigation		Hal Burnett	1539604.73599	10425634.1509		Yes	2,412
C-55			None		W.K. Heagy	1567555.00780	10426216.4483		No	
C-72			Irrigation		George Atkins	1552531.73670	10416783.2315		Yes	2,406
C-88		2,600	Irrigation	900	Western Cotton Oil Co.	1546359.38501	10422839.1238	1957	Yes	2,409
C-83	1951	2,800	None	1,330	Western Cotton Oil Co.	1551250.68258	10422955.5832	1957	No	
C-94	1951	2,727	Irrigation	1,750	Bruce Grammer	1546359.38501	10416899.6910	1955	Yes	2,415
C-98		2,727	Irrigation	1,800	Heagy and Grammer	1544030.19569	10414337.5828	1957	Yes	2,424
C-101		2,600	Irrigation	800	Catholic Foundation	1542982.06050	10418413.6641	1957	Yes	2,419
C-107			Irrigation	800	G.C. Holladay	1539255.35759	10414221.1233	1957	Yes	2,432
C-109	1940	2,600	None	20	George Atkins.	1535412.19522	10410028.5825	1947	No	
C-111			Irrigation		G.C. Holladay	1534946.35736	10409446.2852		Yes	2,447
C-126			Irrigation	1,320	Heagy and Hart	1535062.81682	10415502.1774	1957	Yes	2,431
C-162			Irrigation	800	Reischman	1541933.92531	10404438.5282	1957	Yes	2,445
C-174	1951	2,725	Irrigation	90	George Atkins	1554045.70976	10405020.8255	1957	Yes	2,419
C-181		2,910	None	750	George Atkins	1561615.57504	10406068.9607	1957	No	
D-26	1956	2,700	Irrigation	165	A.E. Simmons	1586304.98180	10426332.9077	1957	Yes	outside of Fairway
D-42	1947	2,855	None	150	Carl Courtney	1597601.54999	10416783.2315	1948	No	
D-61			None	175	Charles Harral	1572562.76483	10396635.7439	1957	No	
H-9		2,570	Irrigation	1,100	George Atkins	1530520.89765	10388600.0408	1950	Yes	2,502
H-36	1940	2,835	Irrigation		R.G Hiner	1524232.08650	10379865.5809		Yes	2,548
H-53		3,000	None	1,320	H. Johnson	1541933.92531	10357738.2823	1950	No	
H-59	1950	1,925	None	10	A.C. Hoover	1558704.08839	10363561.2556	1950	No	
J-5		2,600	None	5	E.C. Powell	1579200.95439	10393957.1762		No	
U-45	1957	2,200	Irrigation	876	M.R. Tripp	1719068.77290	10327342.3617	1957	Yes	outside of Fairway
C-73	1949	2,668	Irrigation		George Atkins	1554708.52032	10416224.6988		Yes	2,405
C-102		2,600	Irrigation	500	Lutaehy	1542715.57047	10416912.8189	1957	Yes	2,421
C-19		2,300	Irrigation		Hal Burnett	1539485.31833	10427680.5230		Yes	2,411
H-37	1944	2,550	Irrigation	2,800	Scripps Farm	1521934.42461	10377102.8244	1948	Yes	2,560
H-38	1946	2,540	Unknown	3,500	Culbertson and Irwin	1521242.76378	10373817.4354	1947	Yes	2,564
H-39	1947		Irrigation		Scripps Farm	1521156.30617	10371310.1649		Yes	2,572
C-20		2,460	None		Tyler	1539053.03031	10428804.4719		No	

ft bgs = feet below ground surface

gpm = gallons per minute

ft amsl = feet above mean sea level

Note: * Some of the wells listed with "No" under the Used column do not have a head elevation and were not included in the simulation.

Source: Pecos County Supply wells is Armstrong and McMillion (1961).

APPENDIX E

San Andres Pumping Records

Appendix E Table 1

Simulated Pumping Rates for San Andres Lea County Water Flood Supply Wells by Layer

Research Partnership to Secure Energy for America

Year	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	1986 - 2010
Stress Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	1 - 25
Well	Pumping Rate (gpm)																									
CP670 L1	121	121	121	121	121	121	121	121	121	121	87	82	67	18	33	4	15	1	1	0	0	0	0	0	0	1,520
CP670 L2	142	142	142	142	142	142	142	142	142	142	102	96	79	22	39	5	17	2	1	0	0	0	0	0	0	1,784
CP670 L3	100	100	100	100	100	100	100	100	100	100	72	68	55	15	27	4	12	1	1	0	0	0	0	0	0	1,252
CP694 L1	0	34	34	34	34	34	34	34	34	34	89	18	22	0	56	55	53	79	3	24	46	49	44	36	17	892
CP694 L2	0	37	37	37	37	37	37	37	37	37	98	20	24	0	61	61	58	86	4	26	51	54	48	39	19	981
CP694 L3	0	37	37	37	37	37	37	37	37	37	97	20	24	0	61	60	58	86	4	26	51	54	48	39	19	978
CP697 L1	0	0	115	115	115	115	115	115	115	115	104	102	82	110	70	90	98	101	68	32	12	19	8	5	2	1,824
CP697 L2	0	0	173	173	173	173	173	173	173	173	156	152	123	165	104	135	147	151	103	47	18	28	12	7	2	2,737
CP697 L3	0	0	241	241	241	241	241	241	241	241	217	212	171	229	145	188	205	210	143	66	25	39	17	9	3	3,808
CP693 L1	0	0	190	190	190	190	190	190	190	190	155	87	20	0	0	0	0	0	0	0	0	0	0	0	0	1,781
CP693 L2	0	0	197	197	197	197	197	197	197	197	161	90	20	0	0	0	0	0	0	0	0	0	0	0	0	1,847
CP693 L3	0	0	257	257	257	257	257	257	257	257	210	118	26	0	0	0	0	0	0	0	0	0	0	0	0	2,409
CP695 L1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CP695 L2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CP695 L3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CP696 L1	0	0	126	126	126	126	126	126	126	126	122	68	62	1	12	0	39	10	0	0	0	0	0	0	0	1,319
CP696 L2	0	0	243	243	243	243	243	243	243	243	236	131	119	1	22	0	75	19	0	0	0	0	0	0	0	2,551
CP696 L3	0	0	263	263	263	263	263	263	263	263	255	141	129	1	24	0	81	20	0	0	0	0	0	0	0	2,756
CP760 L1	0	0	0	0	0	0	0	0	0	53	47	68	77	58	37	41	40	30	26	9	1	10	6	9	11	522
CP760 L2	0	0	0	0	0	0	0	0	0	266	238	344	388	291	186	206	204	151	131	43	7	50	31	45	56	2,637
CP760 L3	0	0	0	0	0	0	0	0	0	169	152	219	247	185	118	131	130	96	84	27	4	32	20	29	35	1,679
CP761 L1	0	0	0	0	0	0	0	37	37	37	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	129
CP761 L2	0	0	0	0	0	0	0	211	211	211	114	0	0	0	0	0	0	0	0	0	0	0	0	0	0	748
CP761 L3	0	0	0	0	0	0	0	181	181	181	98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	642
Total (gpm):	363	470	2,276	2,276	2,276	2,276	2,276	2,705	2,705	3,192	2,828	2,037	1,736	1,097	996	981	1,232	1,044	569	301	215	335	234	217	163	34,795
Total (MG):	191	247	1,197	1,197	1,197	1,197	1,197	1,423	1,423	1,679	1,488	1,071	913	577	524	516	648	549	299	158	113	176	123	114	86	18,301

gpm = gallons per minute

MG = million gallons per year

L1 = Layer 1, Upper San Andres

L2 = Layer 2, Porosity Zone

L3 = Layer 3, Lower San Andres

Note: Pumping rates prior to 1995 were estimated based on the 1995 pumping rate data.

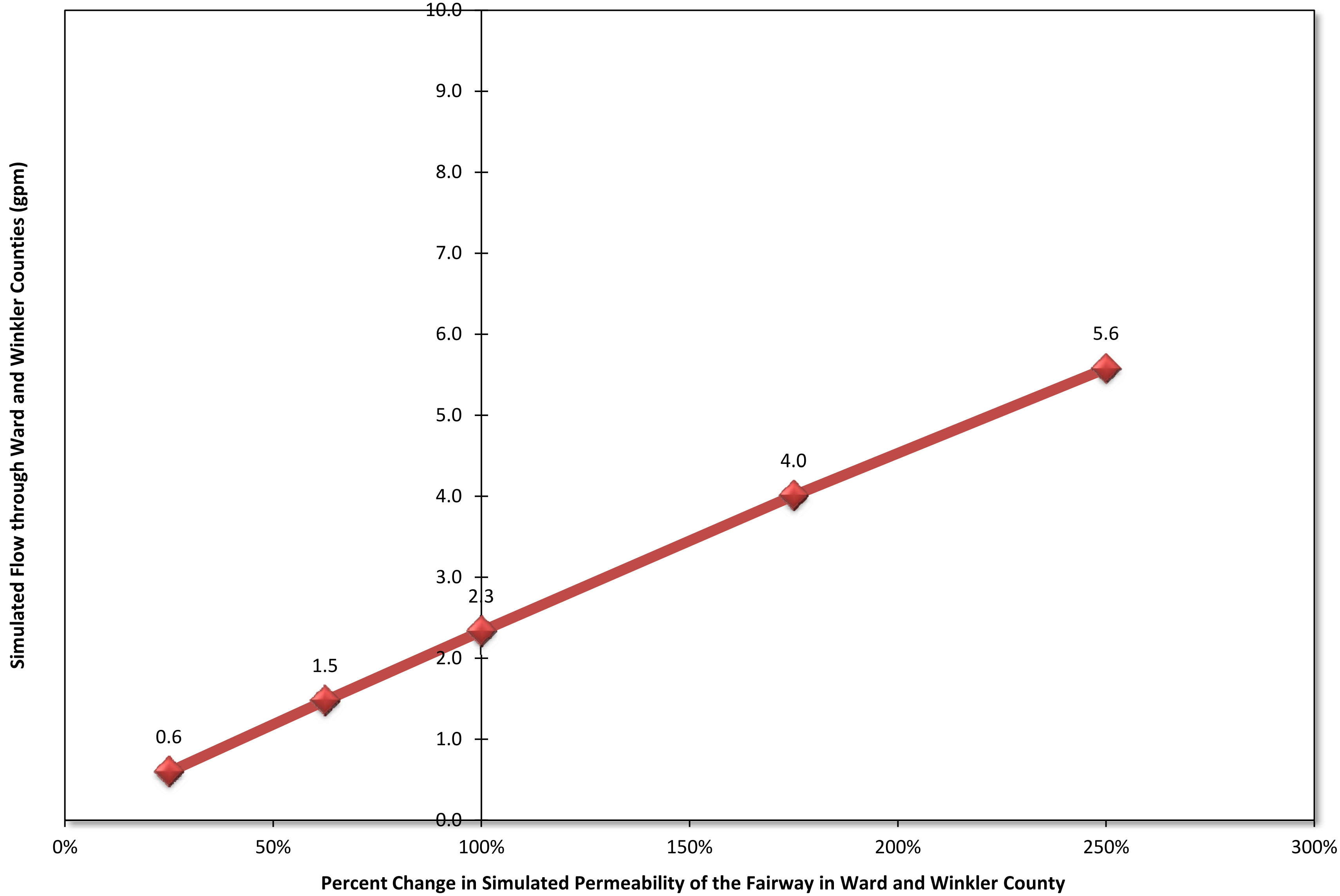
Source: New Mexico Office of the State Engineer WATERS Database (2011)

APPENDIX F
Model Sensitivity Analysis

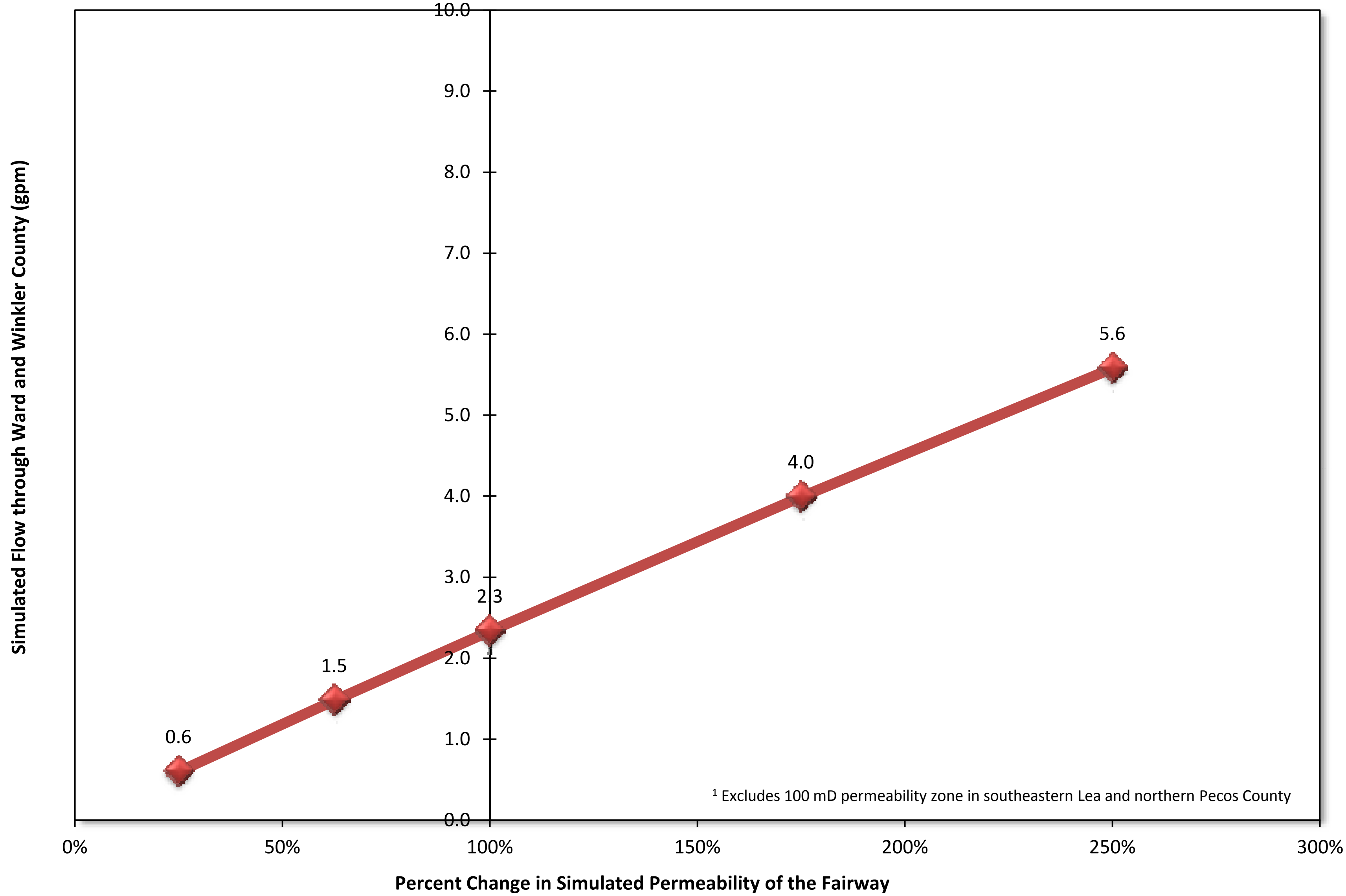
Appendix F Figure F1

Sensitivity to the Permeability of the Fairway in Ward and Winkler County

Research Partnership to Secure Energy for America



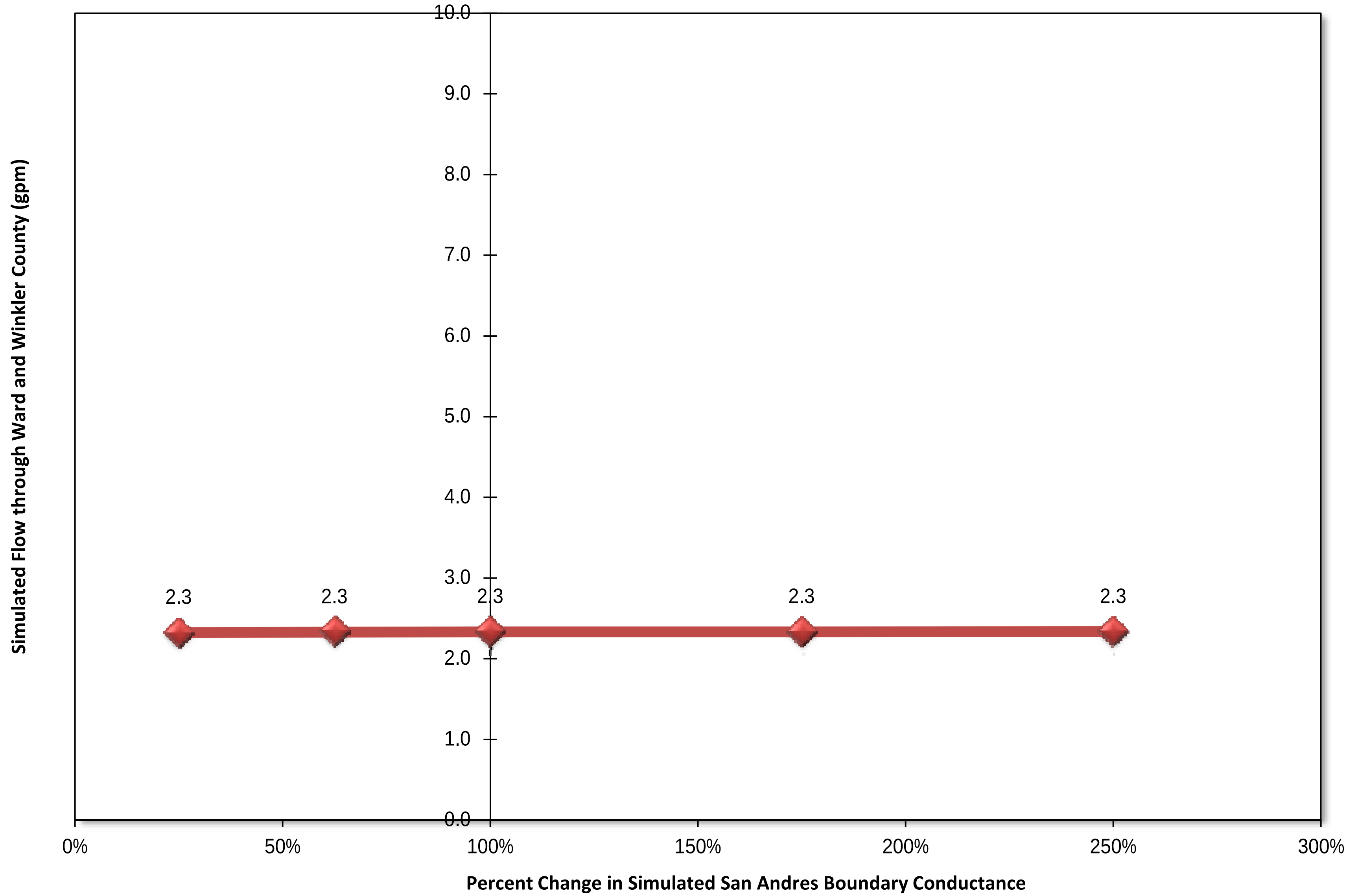
Appendix F Figure F2
Sensitivity to Permeability of the Fairway[1]
Research Partnership to Secure Energy for America



Appendix F Figure F3

Sensitivity to Boundary Conductance of the San Andres Head-Dependant Flux Boundaries

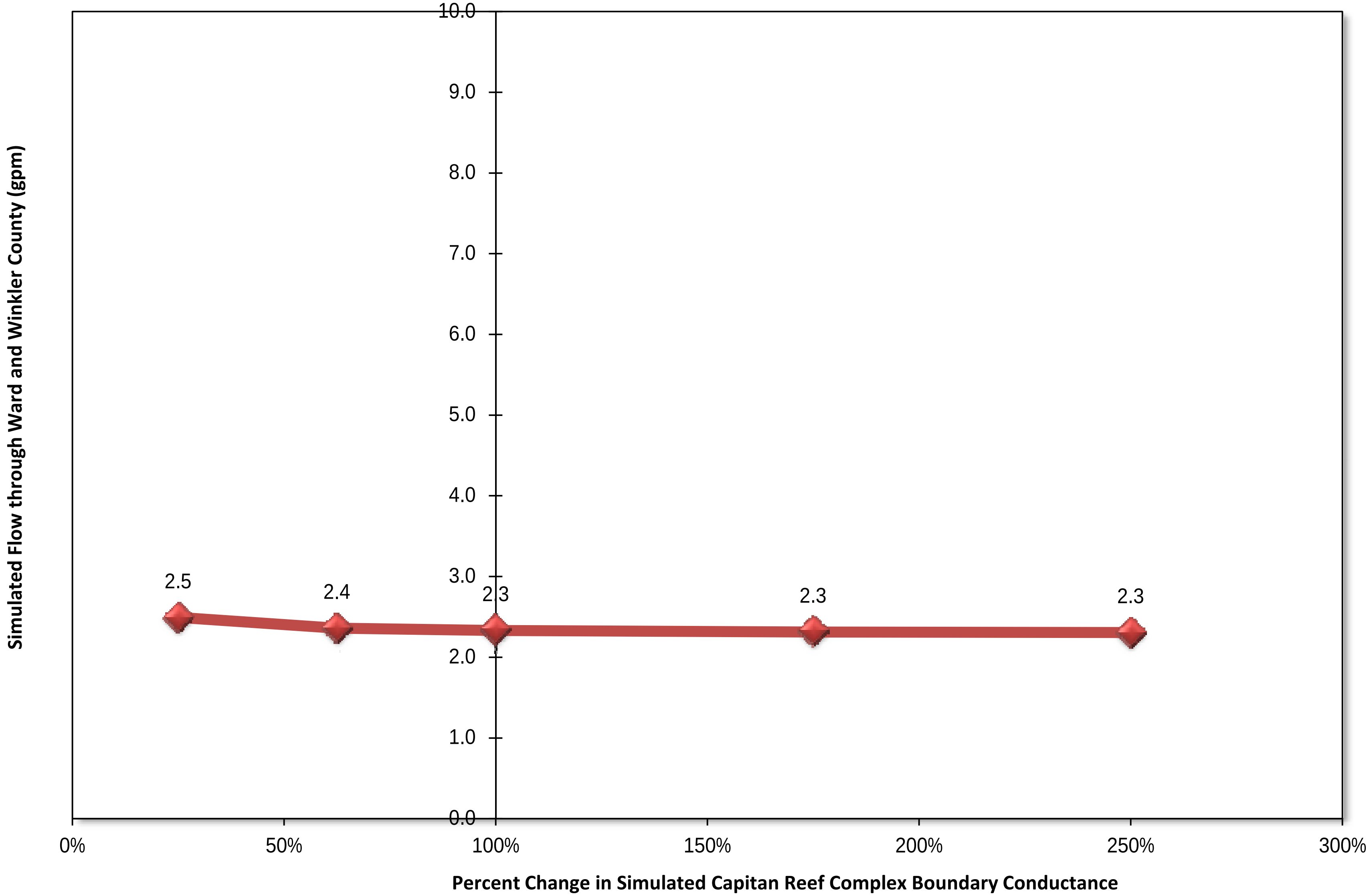
Research Partnership to Secure Energy for America



Appendix F Figure F4

Sensitivity to Boundary Conductance of the Capitan Reef Complex Head-Dependant Flux Boundaries

Research Partnership to Secure Energy for America



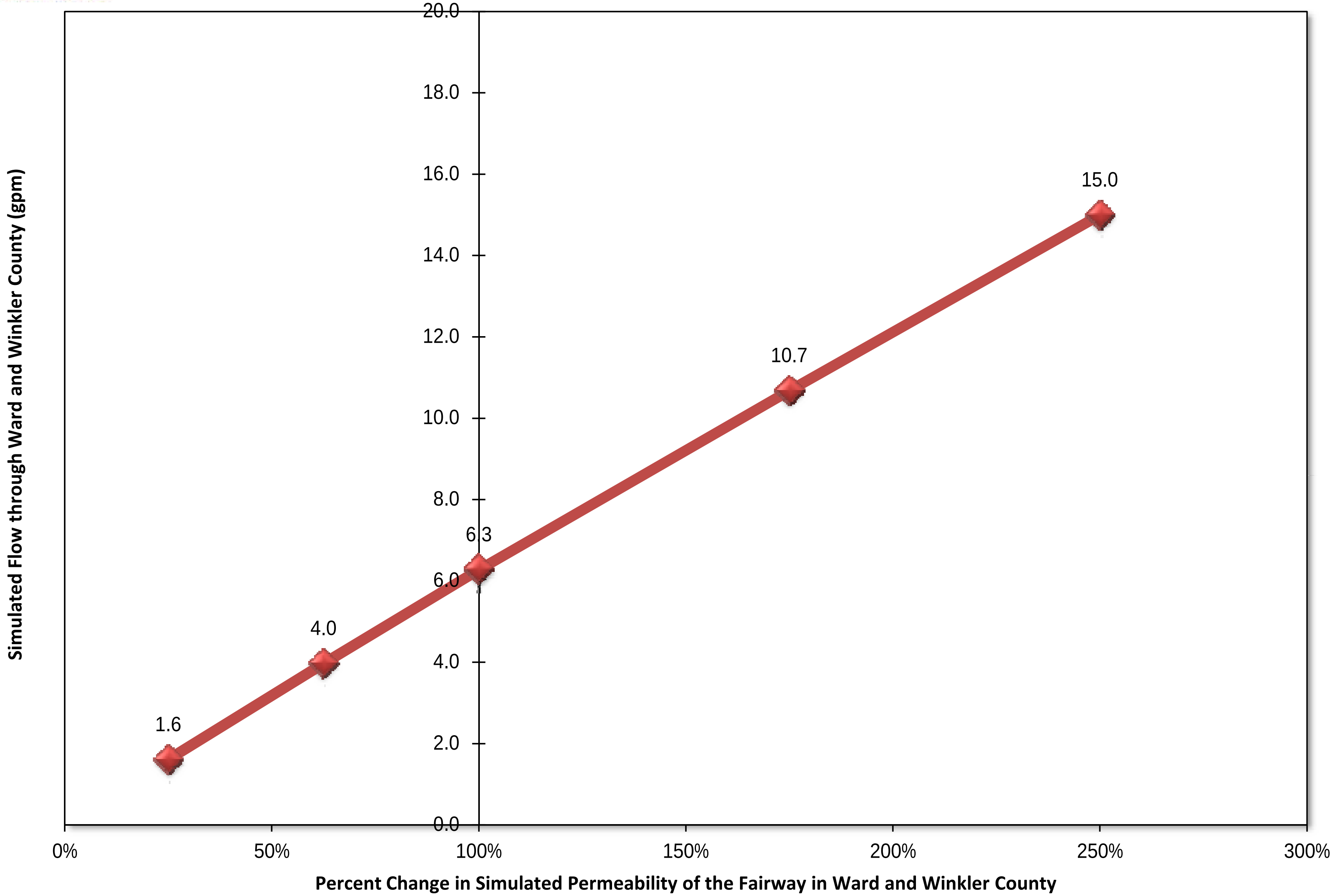
APPENDIX G

Graphical Output of Model Sensitivity Analyses

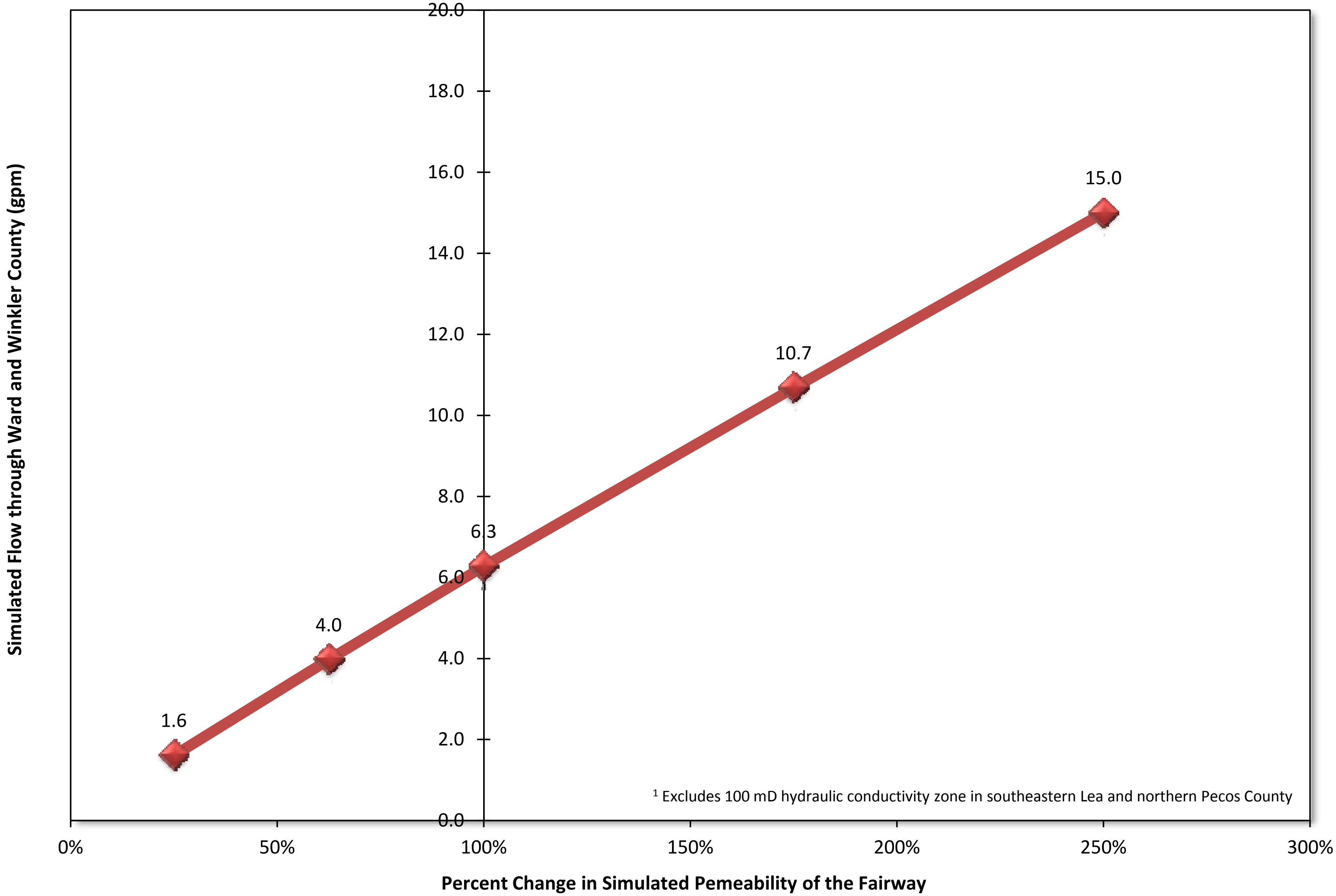
Appendix G Figure G1

Sensitivity to Hydraulic Conductivity of the Fairway in Ward and Winkler County

Research Partnership to Secure Energy for America



Appendix G Figure G2
Sensitivity to Hydraulic Conductivity of the Fairway[1]
Research Partnership to Secure Energy for America

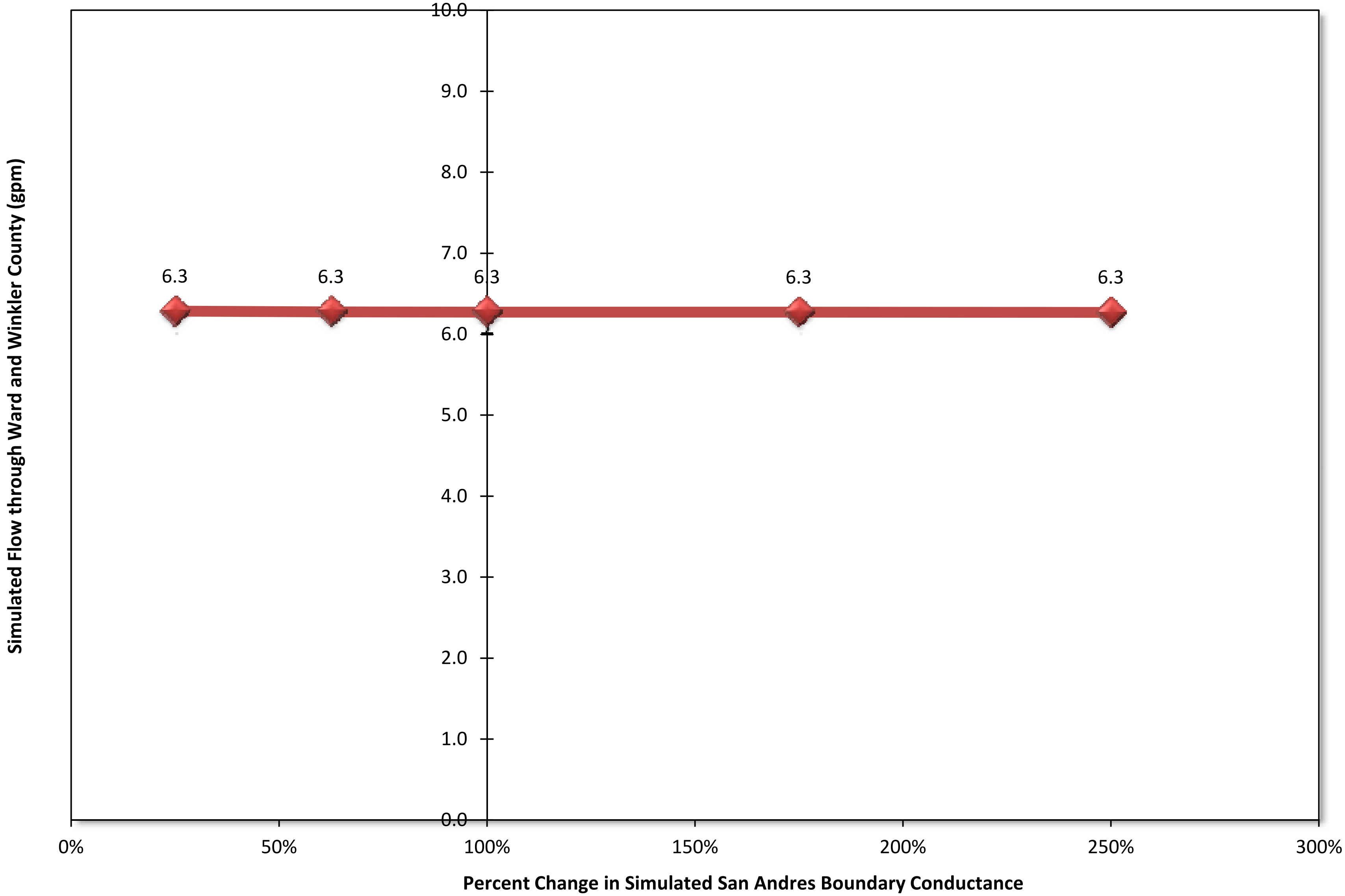


[1] Excludes 100 mD hydraulic conductivity zone in southeastern Lea and northern Pecos County

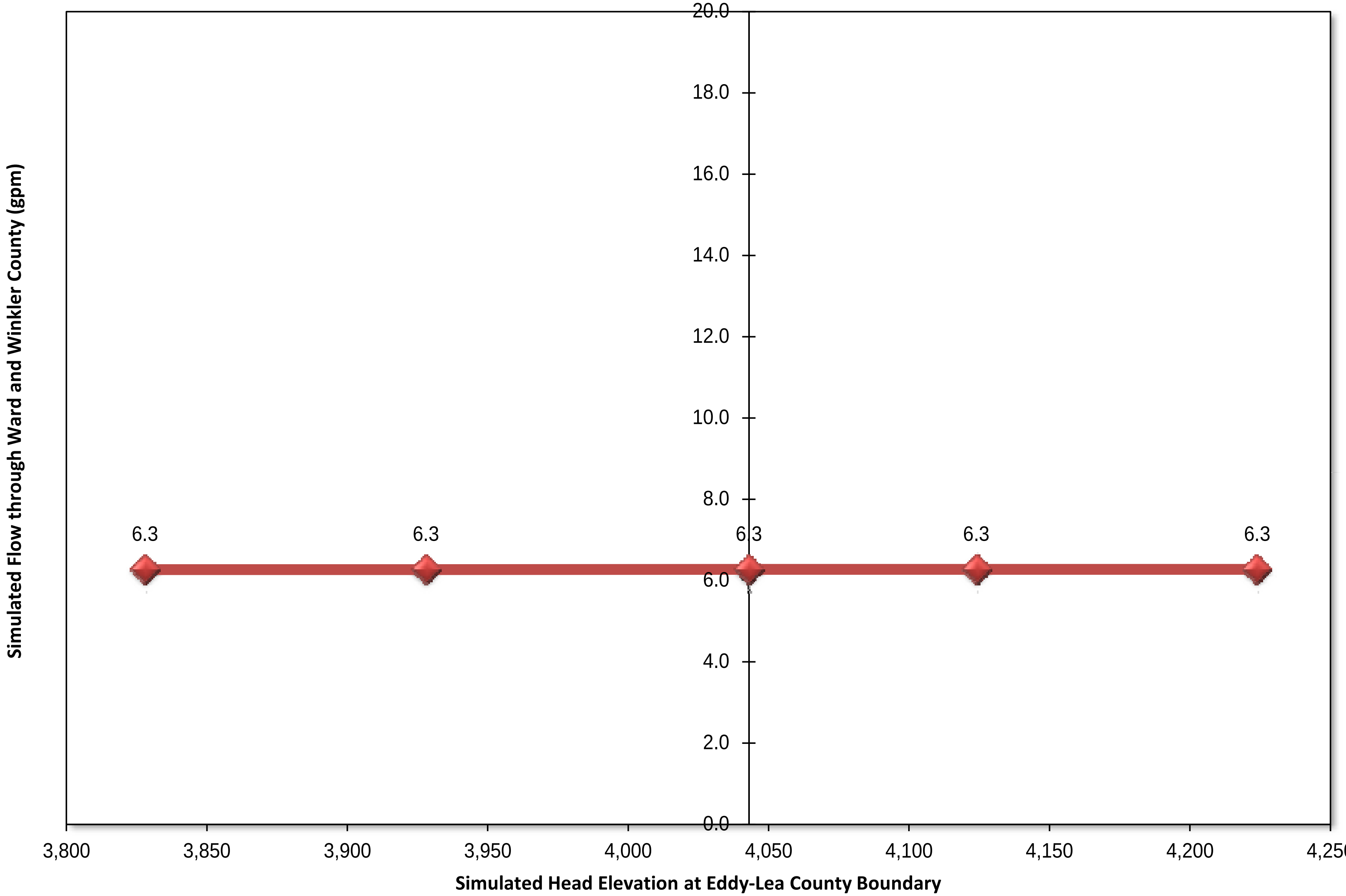
Appendix G Figure G3

Sensitivity to Boundary Conductance of the San Andres Head-Dependant Flux Boundaries

Research Partnership to Secure Energy for America



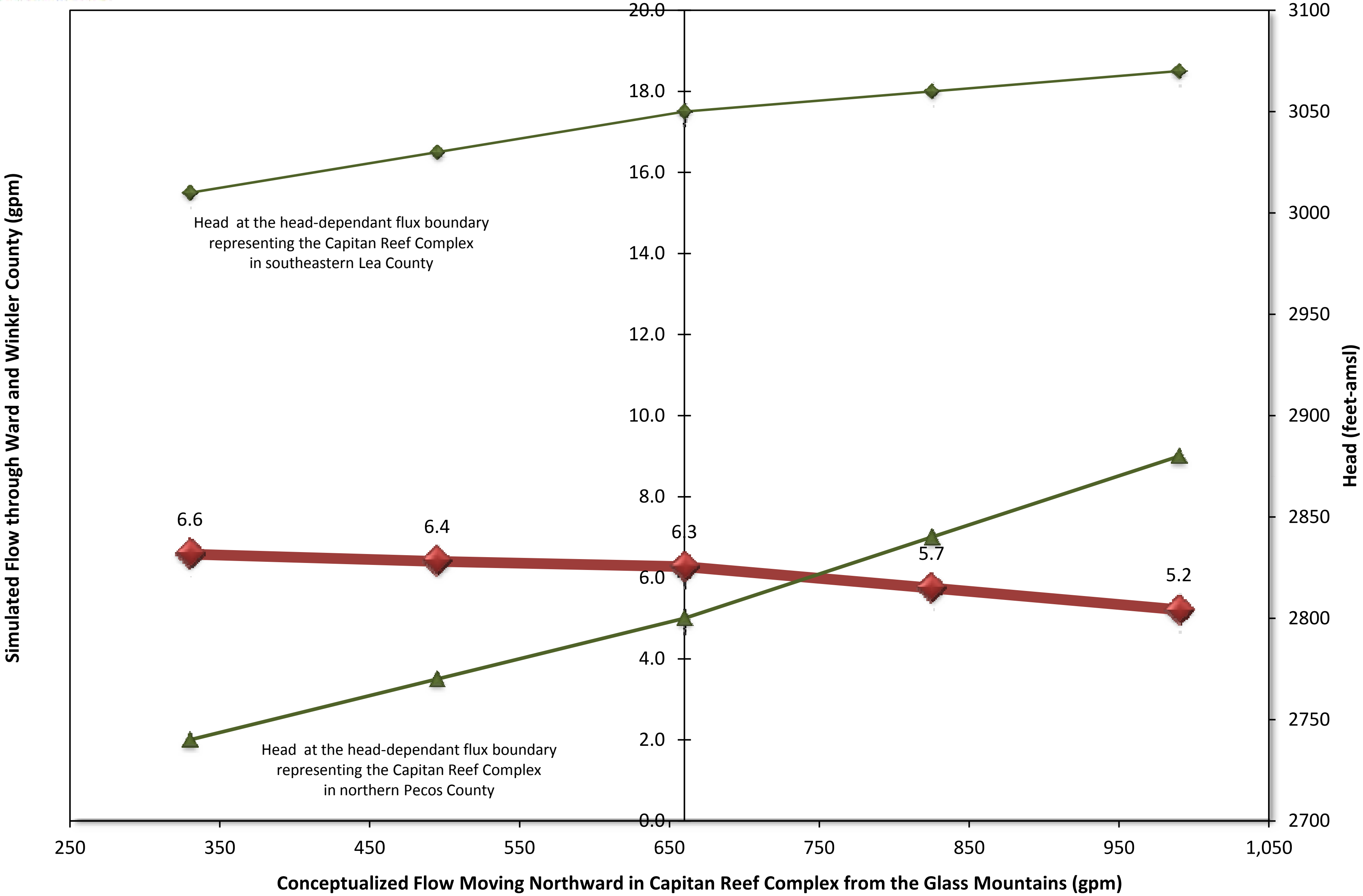
Appendix G Figure G4
Sensitivity to Head Elevation at Eddy-Lea County Boundary
Research Partnership to Secure Energy for America



Appendix G Figure G5

Sensitivity to Recharge to the Capitan Reef Complex in the Glass Mountains

Research Partnership to Secure Energy for America



Appendix G Figure G6
Sensitivity to the Permeability of the Capitan Reef Complex
Research Partnership to Secure Energy for America