Geologic and Hydrologic Controls on Reservoir-Scale Variability in Formation-Water Compositions

Prepared by:

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Principal Investigator: Dr. Alan R. Dutton

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SUMMARY

Subsurface formation waters exhibit regional trends in measured chemistries, but the data also exhibit marked local variance that has not been adequately described or explained. An integrated study of chemical, petrologic, and fluid-pressure data from a well-characterized natural gas field in the Gulf Coast basin will allow us to determine reservoir-scale controls on chemical and diagenetic variability. Understanding the controls on chemistry can provide insight into fluid flow and rock-water interactions in similar geologic settings. Knowledge of solute distributions will aid in the assessment of compartmentalization within reservoirs and fluid communication between reservoirs. Such assessment is relevant not only to improved hydrocarbon exploitation but also to the safe injection of chemical wastes. Finally, understanding small-scale chemical changes would further the interpretation of regional variations in water chemistry, diagenetic facies, and fluid flow within the Cenozoic section of the Gulf Coast basin. This interpretation is potentially important in the study of hydrocarbon migration and entrapment.

We propose to sample in detail formation waters from Stratton Field in Nueces and Kleberg Counties, Texas, in order to map and interpret chemical variations within and between individual reservoirs. The results of water analyses will be mapped with respect to facies and reservoir geometries and features such as faults in order to determine stratigraphic, structural, and hydraulic controls on chemical variability. Hydrochemical data will be compared with mineralogic analyses of core, and geochemical modeling will be conducted. Results will be assessed in terms of the extent of rock-water equilibration to determine plausible reaction and mixing sequences along flow paths.

BACKGROUND

Estimating the salinities and compositions of subsurface waters has long been a major problem for petroleum producers in Texas, and has been the subject of numerous studies (Texas Water Development Board, 1972; Kharaka and others, 1977a, 1978; Land and Prezbindowski, 1981; Stoessell and Moore, 1983; Morton and Land, 1987). Broad compositional trends have been delineated and used as the basis for models of formation-water origin and migration (White, 1965; Kharaka and others, 1977b; Stoessell and Moore, 1983; Loucks and others, 1984; Hanor, 1987b; Morton and Land, 1987; Macpherson, 1989; Macpherson and Land, 1989; Land and Macpherson, 1992a; Bein and Dutton, in press). These models involve processes such as meteoric water influx and solute transport, convection of brine plumes, and chemical changes during water migration. However, water compositions are also highly variable.within the regional trends,

Smaller-scale studies have also indicated that water composition also varies dramatically, both laterally and vertically, within many individual natural gas and oil fields (Fowler, 1970; Morton and Land, 1987; Land and Macpherson, 1992b). This variability has commonly been ascribed to poor-quality data or ambiguities resulting from collection procedures (Carpenter and Miller, 1969; Collins, 1975). More recent studies, however, indicate that improved sampling methods and analytical equipment yield the same highly variable water chemistries. Furthermore, the analyses by different workers are reproducible, proving that the chemical variations within small areas are real (Land and Macpherson, 1992b).

There are three possible natural controls on chemical variation within subsurface waters (Collins, 1975; Hanor, 1987a): (1) differential transport of different species (e.g., as a result of membrane filtration; McKelvey and others, 1959; Fowler, 1970); (2) mixing of waters with different chemistries (Hanor, 1987a, 1987b; Land and others, 1988); and (3) reaction with the host rock (e.g., evaporite deposits; Land and Prezbindowski, 1981). Each of these processes has been inferred as a cause of subregional compositional variation.

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The salinity variations within a field were ascribed by Fowler (1970) to the membrane filtration of migrating formation waters by shales. However, the distributions of species such as lithium, boron, and deuterium within the Gulf Coast basin are opposite from those expected from membrane filtration (Land and Macpherson, 1992a). Morton and Land (1987) concluded that whereas large-scale thermohaline convection causes much of the larger scale variation in water chemistry, local "plumbing," commonly dictated by faults, causes the mixing of different types of water.

Morton and Land (1987) observed that the Cenozoic most clastic reservoirs within the Gulf Coast contain three types of water: Na-acetate, NaCl, and Ca-rich. Land and Macpherson (1992a) illustrate how each of these types reflects reaction with sediments. Na-acetate water tends to be derived from seawater that has been modified by microbial reactions, by loss of Mg during shallow burial, and by the addition of interlayer water from clays during deeper burial. Na-acetate water is characteristic of shale-rich sections and tends to be less saline than waters from sand-rich sections. NaCl water forms as Na-acetate water or meteoric water dissolves diapiric halite. Ca-rich water, which is less common, results from the albitization of plagioclase or the upwelling of water from Mesozoic strata. Most reservoirs produce mixtures of these three types of water. Land and Macpherson (1992b) suggest that many subsurface waters may not be in complete equilibrium with associated reservoir rock.

Four additional sources of variability become factors in oil- and gas-producing fields. One is the addition of water that condenses from natural gas as pressure is reduced within the reservoir and as temperature and pressure are reduced within the wellbore. A second source of change is reaction with the host sediment and within the wellbore (e.g., scaling and corrosion). Third, the sources of produced water may change throughout the life of the well due to the influx of water from the flanks of the producing section (Ghoniem and Al-Zanki, 1987) or to production of water expelled from surrounding shales (Fowler, 1970). The addition of condensed or expulsed water explains why produced formation waters commonly become more dilute during the lifetime of a well (Fowler, 1970; Collins, 1975). Fourth, formation water composition may be artificially

changed as a result of the use of additives (e.g., scale inhibitors, acid or alkali treatments, or surfactants) or flooding with non-native water. All four of these factors must be accounted for when determining the original in-situ composition of produced water.

RATIONALE

Despite the characterization of large-scale chemical trends and of the possible reasons for their occurrence, the factors governing the variability of formation water chemistry at the reservoir scale have not been adequately addressed. Likewise, diagenetic trends within Gulf Coast sandstones have been documented in detail and related to general trends in formation water chemistry (Kaiser, 1984; Morton and Land, 1987; Milliken, 1989), but local variability within and between fields, while observed, has not been well documented. Fluid flow and mixing, and accompanying chemical reactions, can be governed by the presence of local heterogeneities such as faults and shaly interbeds within reservoir sands. Diagenetic alteration, which can enhance or reduce reservoir porosity, has been shown to occur on scales of meters or less (Langford and others, 1990; Sullivan and McBride, 1991).

In the past decade, several studies (e.g., Cherry, 1983; LeBlanc, 1987) have demonstrated the importance of spatially intensive data acquisition for delineating geochemical and hydraulic heterogeneity within aquifers in surficial sediments (less than approximately 300 ft, or 90 m, deep). In studying the Gulf Coast basin, Morton and Land (1987) have stated, "Formation water chemistry will be fully understood only when subregional areas are studied in great detail," adding that elemental and isotopic data from both water and rocks, as well as hydrologic data, are necessary. This proposed study is timely, for as the U. S. Department of Energy (1989) has recently pointed out, opportunities for intensive characterization of native water chemistry at depth are dwindling as oil and gas wells in the lower 48 states are being used for secondary or tertiary recovery or being abandoned outright .

OBJECTIVES

The primary objective of this investigation is to determine controls on local chemical and diagenetic variability by examining chemical, petrologic, and fluid-pressure data in an integrated manner. We propose to study the composition and distribution of brines within a gas-producing field in the Cenozoic section of the Texas Gulf Coast. During the 3-year Secondary Gas Recovery study of Stratton field in Nueces and Kleberg Counties, Texas, funded by the Gas Research Institute, the U.S. Department of Energy, and the State of Texas, we have assembled a unique database, including detailed well histories, a detailed geologic analysis, and 8 mi^2 of three-dimensional seismic data. Stratton is a typical fluvial-dominated Frio Formation (Oligocene) field within the large FR-4 gas play along the Vicksburg fault zone in South Texas (fig. 1) (Kosters and others, 1989). Such fields are well suited for the proposed research: reservoirs are thin channel sandstones, usually less than 30 ft (9 m) thick, separated vertically and laterally by shales (Kerr, 1990; Kerr and Jirik, 1990). Therefore, perforated intervals are short and the sources of water relatively easy to identify. The reservoir section is more than 3,000 ft (900 m) thick and contains more than 300 known reservoirs.

This study will analyze the chemical variation within sandstones and between sandstones in adjacent reservoirs over areas of several square miles. A pilot study of 14 samples has indicated that waters in Stratton field are NaCl-dominated, with maximum total dissolved solids concentrations on the order of 40,000 mg/L. These compositions and relatively dilute concentrations are consistent with the regional trends along the central coast, as delineated by Morton and Land (1987). However, compositional variability within sandstones is as much as 25 percent of the highest salinities, and compositions vary between stratigraphically adjacent sandstones by as much as 50 percent of the highest salinities. The more extensive water sampling envisaged in this project will allow delineation of the local trends in the chemistry of water and its correspondence with the reservoir rock. Results will be mapped and superposed on facies and reservoir geometries and other features such as faults.

In addition, we will compare the chemistry of formation waters with the variations in diagenetic fabrics observed in cores. Prior core analyses conducted for the Secondary Gas Recovery project have revealed that the diagenetic mineralogic assemblage is homogeneous within intervals of approximately 1 ft (0.3 m) (Langford and others, 1990). Formation water chemistry is likely to be uniform over these short distances. However, larger scale diagenetic and depositional variations are evident in cores from different reservoirs in Stratton field. The diagenetic variations coincide with some of the hydrochemical variations; for example, the highest salinities coincide with reservoir rocks containing analcime cement.

METHODOLOGY

Sample Collection

We will collect samples from a maximum of 40 wells in Stratton field. These wells will be selected based on production information obtained from the operator, Union Pacific Resources Corporation. Reservoirs in which water or gas has been injected will be avoided. Wells with multiple completions will not be used because the sources of produced water would not be identifiable. We expect to find three or four reservoirs within Stratton field in which several wells can be sampled. These reservoirs will provide a baseline that will express chemical variability within individual sandstones.

Water samples will be collected using a portable separator. Temperature, pH, and alkalinity, which are unstable parameters, will be measured at the well head immediately after sampling (Lico and others, 1982). Water samples will be analyzed in the laboratory for metallic species; the inorganic anions Cl^-, SO_4^{2-}, Br^-, I^- and S^{2-}; acetate and other aliphatic-acid anions; total organic carbon and total inorganic carbon; and the isotopes ^{18}O, D, ^{13}C, ^{34}S, and ^{87}Sr. The sample collection and analysis protocols for various species are detailed in Table 1.

Table 1.   Sample collection and analysis protocols for dissolved ionic and isotopic species.

Species	Sample bottle	Filtered?	Treatment	Method of analysis
cations	plastic	yes	add 6N HNO_3	ICP-OES
Cl^-	plastic	yes	none	potentiometric titration
SO_4^{2-}	plastic	yes	none	turbidimetry
Br^-, I^-	plastic	yes	none	oxidation spectrophotometry
S^{2-}	glass	no	add 2N Zn-acetate	oxidation and titration
organic acid anions	glass	yes	add $HgCl_2$	catalytic combustion and measurement of CO_2
TIC	glass	no	none	coulometry
TOC	glass	no	add 6N HCl	oxidation and coulometry
$\delta^{18}O$	glass	yes	none	equilibration with CO_2 and mass spectrometry
δD	glass	yes	none	Zn reduction and mass spectrometry
$\delta^{13}C$	glass	yes	add ammoniacal $SrCl_2$ solution	mass spectrometry on CO_2 generated by acidification
$\delta^{34}S$	glass	yes	add 6N HCl and 5% Cd-acetate	mass spectrometry on SO_2 generated by oxidation
$^{87}Sr/^{86}Sr$	plastic	yes	none	ion exchange and mass spectrometry

Correction and Confirmation of Analytical Results

Postproduction chemical changes will be corrected to determine the true preproduction chemical variation. The effect of dilution by water condensed from gas may be corrected using the methods of Carpenter and Miller (1969) and the geothermometric methods of Kharaka and Mariner (1989) and Land and Macpherson (1992b). Resampling selected wells will provide a direct measure of chemical changes occurring with production. We will resample eight wells for cations and anions twice yearly over a 2-year period. Compositional trends, where linear, will be extrapolated backward to estimate original water chemistry. These estimates will be compared with those derived from geothermometry and dilution calculations. Land and Macpherson (1992b) suggest that the most commonly used geothermometers may be of limited utility. However, well resampling and the methods of Carpenter and Miller (1969) will provide independent checks on the geothermometric calculations.

Integration with Geologic and Petrographic Data

The results of analyses on water samples collected by the Bureau will be integrated with chemical data collected for Union Pacific Resources. The combined information will be plotted on maps and cross sections of the field that will illustrate the distribution of sandstone and shale and the locations of faults. Net-sandstone maps and depositional-facies maps of many reservoirs have already been prepared and integrated with fault and stratigraphic data to create three-dimensional images of reservoirs in Stratton field. Samples collected in the area covered by the three-dimensional seismic database can be correlated to features on the seismic amplitude maps. Maps and cross sections will be used to delineate potential flow and mixing paths for waters with different compositions, along with the locations of potential barriers to flow, within and between reservoirs. Compositional variations will be compared with pressure distributions within individual reservoirs in order to map potential compartments.

Petrographic samples will be taken from core holdings of Union Pacific Resources and/or of the Core Research Center of the Bureau of Economic Geology. Thin sections from cores will

be point counted to determine the mineral species present. Petrographic analysis, including clay mineralogy, has already been performed on three cores from Stratton field, and they contain a heterogeneous collection of sandstones with variable framework and diagenetic compositions. Diagenesis in some reservoirs is dominated by calcite-chlorite cementation (Grigsby and Kerr, 1991), whereas other reservoirs contain calcite-analcime cements or elemental sulfur and analcime cement. Carbonates extracted from the cores will be analyzed for $^{87}Sr/^{86}Sr$, $\delta^{13}C$, and $\delta^{18}O$. Microprobe analyses will be conducted to determine the compositions of authigenic and detrital feldspars.

Analysis of Results

End-member compositions for waters in the reservoirs will be determined and chemical gradients will be mapped. Solute speciation and saturation states will be calculated using programs such as PHRQPITZ (designed for speciation in brines; Plummer and others, 1988) and SOLMINEQ.88 (designed for speciation in oil-field waters; Kharaka and others, 1988). The data base for PHRQPITZ will be modified to incorporate thermodynamic data for aluminum from Crowe and Longstaffe (1987) and Crowe (1988). The minerals identified from petrographic analysis of the cores will be matched to the results of these calculations to determine which minerals are at equilibrium with associated water. Plausible reaction and/or mixing sequences will subsequently be determined along possible flow lines.

In addition to the geological mapping and interpretation, the chemical/isotopic data will be evaluated by graphical and statistical techniques. Dutton and others (1989) have shown that graphs of ionic ratios and of stable isotopic composition are useful for delineating sources of saline fluids. Cluster analysis may be used as an exploratory tool to divide samples into groups based on chemical composition. Principal component analysis and multiple discriminant analysis may be used to identify the factors that best explain spatial variability and account for end-member waters. Proposed flow paths will be evaluated in light of the graphical and statistical analyses.

INDUSTRY COOPERATION

Union Pacific Resources Corporation has already provided pressure data, chemical data, production histories, and well logs. The company has verbally agreed to allow us continued access to its wells in Stratton field for sampling and will provide a list of singly-completed, water-productive wells. Sampling by the Bureau will be coordinated with FESCO, which regularly monitors wells in Stratton field on behalf of the operator.

SCHEDULE AND BUDGET

This project will require 3 years for completion (fig. 2). The first year will focus on collection and analysis of water samples from Stratton field and on petrographic study of core. The second year will be devoted to collection and analysis of water samples from the remaining wells; completing petrographic study of core; preparation of maps of chemical variation; and geochemical modeling. Maps of pressures in selected reservoirs and groups of reservoirs will be prepared in year 2. Further stratigraphic analysis will require 4 months and will be completed within the first 2 years. In year 3, geochemical modeling will continue and statistical analysis of results will be conducted. Staff scientists will include one hydrologist (the principal investigator), one stratigrapher, one hydrochemist, and one petrographer.

QUALIFICATIONS

The principal investigator, Dr. Alan R. Dutton, has over 10 years experience at the Bureau of Economic Geology in studying the hydrogeology of sedimentary basins and the geochemistry of ground water and brine. His work has included modeling of fluid flow and chemical speciation and the statistical analysis of geologic data. Dr. Richard P. Langford, who will serve as the stratigrapher for the project, has spent four years studying the stratigraphy of the Frio Formation as part of the Secondary Gas Recovery Project. Dr. Alan E. Fryar, who will serve as the project hydrochemist, has spent four years modeling diagenetic reactions accompanying fluid flow through sediments. The professional summaries for these three researchers, including lists of
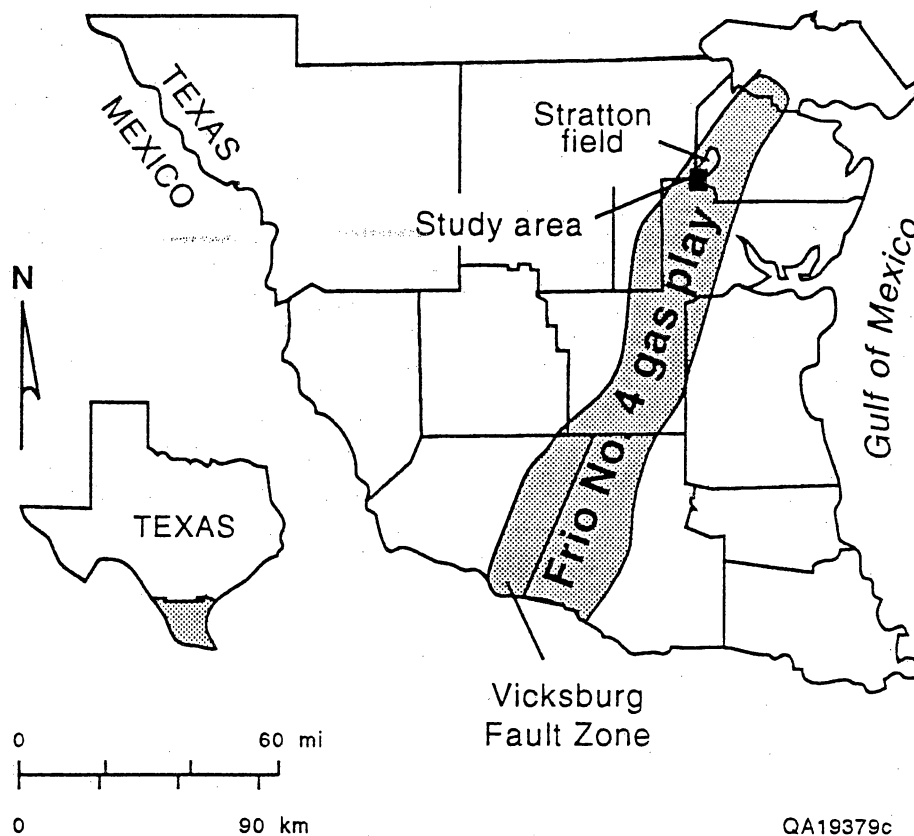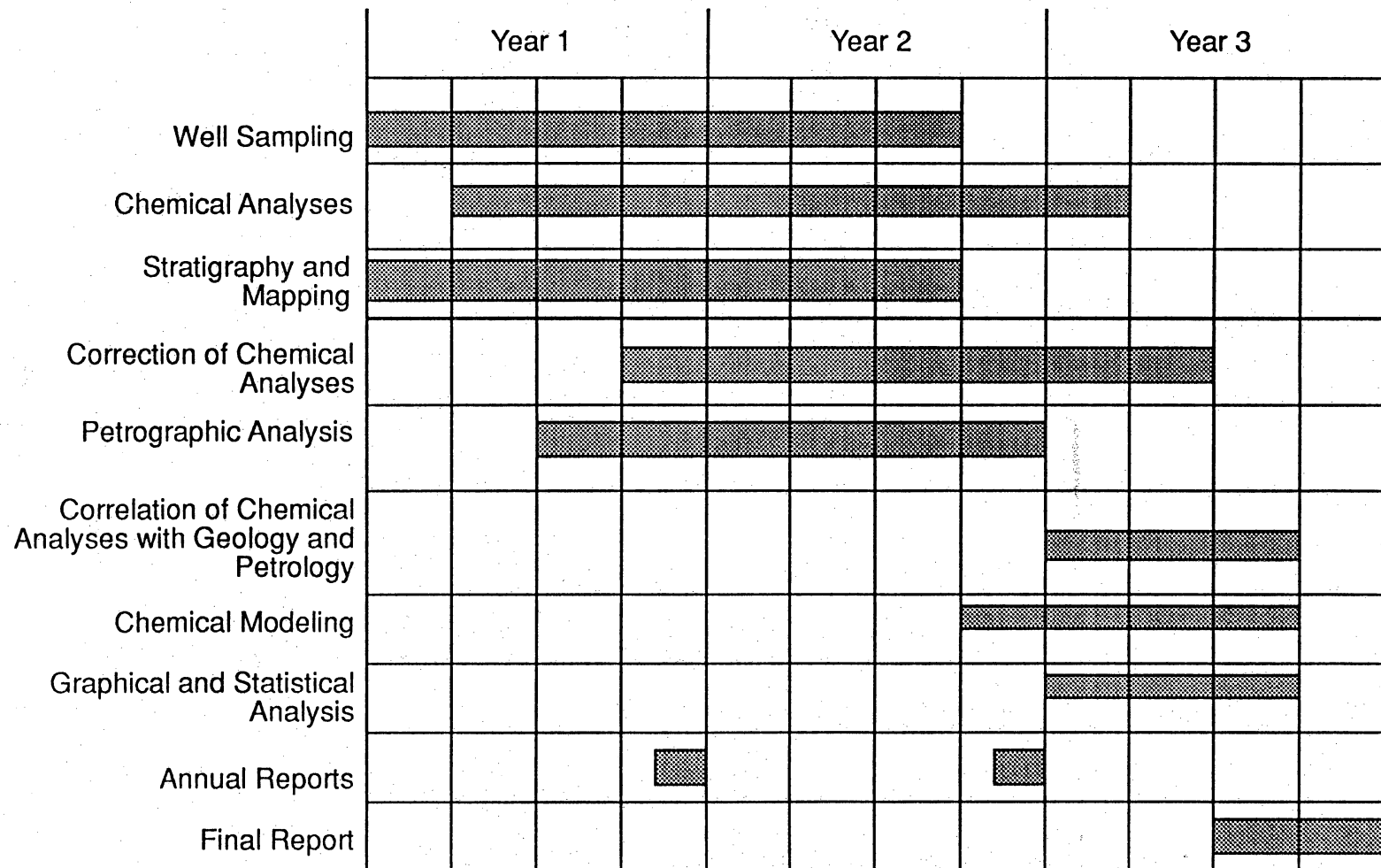
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Figure 1. Location map of major Frio Formation gas fields containing fluvial-deltaic reservoirs in the on-shore Gulf Coast basin of Texas (from Levey and others, 1992).

Figure 2. Bar chart showing time allocated for project tasks.

publications, are attached. In addition, another Bureau scientist will be added as project petrographer.

FACILITIES AND RESOURCES

The Bureau of Economic Geology was established in 1909 by the University of Texas. The Bureau is a major research unit of the University and functions as a quasi-state agency, the state geological survey of Texas. In 1985 a new research complex for the Bureau was completed at the University's Balcones Research Center in Austin. The Bureau's modern facilities include a building for research and administration (150,000 square feet), the Mineral Studies Laboratory (35,500 square feet), and the Core Research Center (101,500 square feet).

The Bureau is currently involved in about 50 separate research projects funded by federal, state, and private entities. The research staff includes over 60 geologists, engineers, chemists, and resource economists. Active projects include geologic mapping; energy resources and energy policy; land, environmental, and geohydrologic studies; structural geology and geodynamics; computer applications; geomorphology and Quaternary stratigraphy; coastal and marine resources; nonfuel mineral resources; and energy and mineral statistics. Results of Bureau work are disseminated through bulletins, reports, and maps published by the Bureau (over 2,100) and by numerous articles published in national and international peer-reviewed journals. Researchers at the Bureau are supported by a full-time administrative staff as well as by professional cartographers, editors, proofreaders, computer scientists, and technicians.

Core Facility

The Core Research Center at the Bureau of Economic Geology is a repository that contains core more than 4,000 wells, mostly from Texas. The facility includes rooms for core viewing and preparation, and the capacity for on-site core slabbing, photography, and thin-section preparation.

Chemical Laboratories

The Mineral Studies Laboratory has an array of modern analytical equipment and state-of-the-art instrumentation. Capabilities include inductively coupled plasma optical and mass spectrometry (ICP-OES, ICP-MS) for major, minor, and trace element measurements; stable isotope mass spectrometry (hydrogen and oxygen in waters, carbon and oxygen in carbonate materials); electron microprobe analysis (four automated wavelength dispersive X-ray spectrometers); scanning electron microscopy (SEM) examination and photography; X-ray diffractometry (XRD) for mineral identifications, ion chromatography (IC); gas chromatography (GC); and other wet chemical techniques.

Computing Capability

The computer resources section supports programming and data base applications on the Bureau's computer system and on the University's IBM, VAX, and Cray computer systems. The Bureau maintains a VAX-VMS cluster, one ULTRIX workstation, two UNIX workstations, and numerous Macintosh desktop computers. New 486 and 386 personal-computer-based workstations support mapping programs to create reservoir models . Software available includes the PHRQPITZ and SOLMINEQ.88 programs for determining speciation and saturation indices.

Alan R. Dutton

Professional Summary

January 1993

Academic Background

B.A. Geology, University of Rochester, 1975
Ph.D. Geology, The University of Texas at Austin, 1982

Areas of Expertise

A. Hydrogeology of sedimentary basins; paleohydrology; hydrology of subsurface
brine; flow in the unsaturated zone; hydrologic measurement techniques;
numerical modeling of regional aquifers.

B. Geochemistry of brine and dilute ground water; isotope hydrology; geochemical
modeling techniques.

C. Statistical analysis of geologic data.

Professional Work Experience

A. The University of Texas at Austin, Bureau of Economic Geology: Research
Scientist and Deputy Associate Director (February 1982 - present)

B. Research and Planning Consultants, Austin, Texas: Research Associate (February
1976 - October 1977)

Professional Activities

Professional Hydrogeologist Certification, American Institute of Hydrology Certificate
No. 867.

Editor, *The Hydrogeologist*, 1990-present, Newsletter of the Hydrogeology Division,
Geological Society of America.

Editorial Board, *Ground Water*, 1988-1990, Journal of Association of Ground Water
Scientists and Engineers.

Professional Societies

American Geophysical Union, Member
Austin Geological Society, Member
Geological Society of America, Fellow
National Ground Water Association, Member

Selected Publications - Last 5 Years

Gustavson, T. C., Hovorka, S. D., and **Dutton, A. R.**, submitted, Origin of satin spar veins in evaporite basins: Journal of Sedimentary Petrology.

Bein, Amos, and **Dutton, A. R.**, in press, Origin, distribution, and movement of brines in the Permian Basin (U.S.A.): a model for connate brine displacement: Geological Society of America Bulletin.

Raney, J. A., and **Dutton, A. R.**, 1990, Geologic and geohydrologic studies near Fort Hancock, Texas: Recent investigations of the proposed site of the Texas low-level readioactive waste repository: West Texas Geological Society v. 30, no. 4, p. 5-10.

Dutton, A. R., 1990, Vadose-zone recharge and weathering in an Eocene sand deposit, East Texas, U.S.A.: Journal of Hydrology, v. 114, p. 93-108.

Richter, B. C., **Dutton, A. R.**, and Kreitler, C. W., 1990, Identification of sources and mechanisms of salt-water pollution affecting ground-water quality: a case study, West Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 191, 43 p.

Dutton, A. R., 1989, Hydrogeochemical processes involved in salt-dissolution zones, Texas Panhandle, U.S.A.: Hydrological Processes, v. 3, p. 75-89.

Dutton, A. R., Richter, B. C., and Kreitler, C. W., 1989, Brine discharge and salinization, Concho River watershed, West Texas: Ground Water, v. 27, no. 3, p. 375-383.

Dutton, A. R., and Simpkins, W. W., 1989, Isotopic evidence for paleohydrologic evolution of ground-water flow paths, southern Great Plains, United States: Geology, v. 17, p. 653-656.

Jorgensen, D. G., Downey, Joe, **Dutton, A. R.**, and Maclay, R. W., 1988, Regional hydrogeology of the Nonglaciated Great Plains, in Back, William, Seaber, P. R., and Rosenshein, J. S., eds., Ground Water Hydrogeology: Geological Society of America, Geology of North America v. O-2, in press.

Dutton, A. R., 1987, Hydrogeologic and hydrochemical properties of salt- dissolution zones, Palo Duro Basin, Texas Panhandle — preliminary assessment: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 87-2, 32 p.

Dutton, A. R., 1987, Origin of brine in the San Andres Formation, evaporite confining system, Texas Panhandle and eastern New Mexico: Geological Society of America Bulletin, v. 99, no. 1, p. 103-112.

Dutton, A. R., Kreitler, C. W., and Gustavson, T. C., 1987, Regional hydrogeologic research in the Palo Duro Basin for nuclear-waste repository siting: Association of Engineering Geology Bulletin, v. 24, no. 2, p. 221-225.

Recent Public Lectures

Simulation of Ground-Water Particle Paths in an Alluvial Aquifer Overlying the Superconducting Super Collider (SSC) Site, Texas; and Paleohydrology of the Non-

Glaciated Great Plains: An Isotopic and Age-dating Study: presented to The University of Southwestern Louisiana, Department of Geology, Lafayette, Louisiana, 1992.

Paleohydrologic evolution of basin-scale flow and associated transport based on the geochemical record: presented at Geological Society of America Penrose Conference on Flow and Associated Transport in Basins: Driving Forces, Coupling and Geologic Controls, 1991.

Isotopic evidence for paleohydrologic evolution of ground-water flow paths, southern Great Plains, United States: presented to University of Kansas, Department of Geology and Kansas Geological Survey, April 1991.

Application of hydrogeochemistry and stable isotopes in confirming conceptual models of ground-water flow: presented as Peggy Lyons Lecture, University of Rochester, Department of Geological Sciences, September 1989.

Alan E. Fryar

Professional Summary

January 1993

Academic Background

B.S. *cum laude*, Geology and History, Duke University, September 1984
M.S. Geology, Texas A&M University, August 1986
Ph.D. Geology, University of Alberta, November 1992

Areas of Expertise

A. Experimental modeling of fluid flow and solute transport with reactions.

B. Mathematical modeling of fluid flow, solute transport, and speciation.

C. Monitoring of ground-water movement and contamination at field sites.

Recent Professional Work Experience

A. The University of Texas at Austin, Bureau of Economic Geology: Research Associate (January 1992–present)

B. Department of Geology, University of Alberta: Research Assistant (May 1987–August 1988; September 1990–December 1991)

C. Department of Geological Sciences, The Ohio State University: Research Assistant (January 1989–August 1990)

Professional Societies

American Geophysical Union
The Geochemical Society
National Ground Water Association
Society of Petroleum Engineers

Awards and Honorary Societies

W. G. Mills Memorial Fellowship in Hydrology, Texas Water Resources Institute, Texas A&M University, 1985–1986

Davidson Fellowship, Graduate College, Texas A&M University, 1984–1985

Dean's List, Duke University, 1981–1984

Class Honors, Duke University, 1981–1982

Phi Eta Sigma (Freshman Honorary), Duke University, 1981–1982

National Merit Scholarship, Duke University, 1981–1982

Publications - Last 5 Years

Articles

Fryar, A. E., and Domenico, P. A., 1989, Analytical inverse modeling of regional-scale tritium waste migration: Journal of Contaminant Hydrology, v. 4, no. 2, p. 113–125.

Abstracts

Fryar, A. E., and Schwartz, F. W., 1992, Experimental modeling of reaction-front evolution in ferric-calcareous sand columns: Geological Society of America, Abstracts with Programs, v. 24, no. 7, p. A128.

Mullican, W. F., III, and **Fryar, A. E.,** 1992, Characterization and modeling of flow and reaction in a perched aquifer at the Pantex Plant, Texas: Eos (Supplement), v. 73, no. 43, p. 235.

Mullican, W. F., and **Fryar, A. E.,** 1992, The role of a perched aquifer in contaminant transport at a proposed superfund site on the Southern High Plains of Texas: Geological Society of America, Abstracts with Programs, v. 24, no. 7, p. A252.

Fryar, A. E., and Schwartz, F. W., 1991, Physical modeling of contaminant-induced diagenesis in a sand aquifer: Eos (Supplement), v. 72, no. 17, p. 124.

Fryar, A. E., and Schwartz, F. W., 1990, Small-scale hydraulic conductivity measurements on sediments in a reaction-transport study: Society of Exploration Geophysicists Research Workshop on Permeability, Fluid Pressure and Pressure Seals in the Crust, Technical Abstracts, p. 49.

Chapters, Sections

Fryar, A. E., 1990, Self-organization in hydrogeologic systems, *in* Domenico, P. A., and Schwartz, F. W., Physical and chemical hydrogeology: New York, John Wiley & Sons, Section 15.4, p. 561–563.

Dissertation

The geochemical and hydraulic evolution of reaction fronts in sand columns: Edmonton, Alberta, Canada, University of Alberta, Ph.D. dissertation, 190 p., 1992.

Recent Public Lectures

The geochemical and hydraulic evolution of reaction fronts in sand columns: presented at the Bureau of Economic Geology Colloquium, The University of Texas at Austin, November 1992.

Characterizing ground-water flow at a U.S. nuclear site: presented to the Department of Geology, University of Alberta, Edmonton, Alberta, Canada, November 1992.

Experimental modeling of contaminant-induced diagenesis: presented to the Department of Geological Sciences, The University of Texas at Austin, October 1992.

Experimental modeling of porous media patterning with heterogeneous reaction fronts: presented to the Bureau of Economic Geology, The University of Texas at Austin, February 1991.

Richard P. Langford

Professional Summary

January 1993

Academic Background

B.A. Colorado College, June 1979
M.A. Indiana University, December 1982
Ph.D. University of Utah, June 1989

Areas of Expertise

A. Stratigraphy, determination of sandstone body geometries, determination of the connectivity between sandstone bodies.

B. Sedimentation, interpretation of depositional environments, mapping depositional environments in the subsurface.

C. Modern depositional processes and deposits.

D. Clastic petrography and the correlation of petrographic changes to depositional facies changes.

Professional Work Experience

Present Position: The University of Texas at Austin, Bureau of Economic Geology: Research Associate (January 1989-present)

Awards and Honorary Societies

Indiana University Fellowship, 1980-1981
Getty Oil Company Scholarship, 1978-1979
Phi Kappa Phi

Selected Publications - Last 5 Years

Langford, R. P., and Chan, M. A., in press, Downwind changes through an ancient dune sea, Permian Cedar Mesa Sandstone, SE Utah: *in* Modern and Ancient Eolian Depositional Environments. International Association of Sedimentologists Special Publication.

Levey, R. A., Sippel, M. A., Finley, R. J., and **Langford, R. P.**, 1992, Stratigraphic compartmentalization within gas reservoirs: examples from fluvial-deltaic reservoirs of the Texas Gulf Coast: Bulletin of the South Texas Geological Society, v. 33, p. 7-16.

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Speaker and organizer, Reservoir properties from core and log analysis of Gulf Coast sandstone reservoirs, Workshop at the 33rd Annual Symposium of the Society of Professional Well Log Analysts, Oklahoma City, June 1992.

Speaker, Short Course, Infield Gas Reserve Growth Potential: Gulf Coast Sandstone Reservoirs (Frio, Vicksburg, Wilcox), Sponsored by the Gas Research Institute, U.S. Department of Energy, and the Bureau of Economic Geology, October 1991. Presented on 5 occasions in Houston, Texas, Corpus Christi, Texas, and Midland, Texas.

Co-Leader, Gulf Coast Association of Geologic Societies field trip number 2, Core and log analysis of depositional systems and reservoir properties of Gulf Coast natural gas reservoirs: an integrated approach to infield reserve growth in Frio, Vicksburg, and Wilcox Sandstones, October 1991.

Speaker, Houston Geological Society, Depositional and diagenetic fabric of gas reservoirs in the Oligocene Vicksburg Formation, McAllen Ranch field, Hidalgo County, Texas, April1991.

Co-Leader, field trip, Erg and erg margin deposits, SEPM Eolian Research Conference, Moab, Utah, August 1990.

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Estimated cost breakdown:

<u>Equipment:</u>

An Apple Macintosh IIsi computer with a color monitor, an 80 Mb hard drive, and 5 Mb RAM will be purchased in year 1. The cost of $2,575 is based upon prices in the fall of 1992 (note that tax is not incurred because the University is tax-exempt); it is conceivable that prices will have fallen further by the time of purchase. This microcomputer will be used by R. P. Langford for his work on project stratigraphy.

<u>Materials and services:</u>

1. Rent for portable separator:

A portable separator will be required to extract formation waters from producing wells. These devices rent for approximately $500 per day. We are estimating a maximum of 36 days (19 days in year 1, 17 days in year 2) to collect 72 samples (including resampling) for a total of $18,000. It may be possible to coordinate our sampling with sampling performed by FESCO, who would have arranged for a separator for themselves, so that we would only pay for any excess time incurred. This would reduce our rental costs.

2. Chemical analysis costs:

a. Water samples

(1) Cations (to be performed at Mineral Studies Laboratory (MSL), Bureau of Economic Geology)	$26
(2) Sulfide (MSL)	$20
(3) Chloride (MSL)	$8
(4) Sulfate (MSL)	$18.75
(5) Bromide (MSL)	$20
(6) Iodide (MSL)	$10
(7) Total inorganic carbon (Controls for Environmental Pollution (CEP), Santa Fe, NM)	$50
(8) Total organic carbon (CEP)	$25
(9) Aliphatic-acid anions (Core Laboratories, Corpus Christi, TX)	$250
(10) Oxygen-18 and deuterium (MSL)	$75
(11) Carbon-13 (including prep.) (MSL)	$62
(12) Sulfur-34 (University of Arizona) (including prep. by MSL)	$90
(13) Strontium-87/86 (Geochron Laboratories, Cambridge, MA)	$250

8 wells will be sampled in year 1 and analyses conducted for all 13 constituents @ $904.75 each = $7,238 total
32 other wells will be sampled (22 in year 1, 10 in year 2) and analyses conducted for constituents 1-10 @ $502.75 each = $11,060.50 total
8 wells will be resampled 4 times each (once in year 1, 3 times in year 2) and analyses conducted for constituents 1-6 @ $102.75 each = $3,288 total

b. 20 core samples will be analyzed for strontium-87/86 @ $250 per sample and carbon-13 and oxygen-18 @ $47 for both isotopes per sample: 20 x $297 = $5,940 (year 2)

c. Microprobe analyses will be conducted on feldspars in 40 thin sections from core: ($61/hr instrument charges) x (2 hr per thin section) x 40 = $4,880 (year 2)

d. Clay XRD analyses: 20 qualitative analyses @ $100 each
                      + 7 semiquantitative analyses @ $315 each= $4,205 (year 2)

2. Thin-section preparation: 100 samples @ $12 each = $1,200

Travel expenses

1. Field work:

(calculations assume 400 miles round-trip to Stratton field, and 100 miles travel per day while in field, @ $0.275/mile;
per diem of $60/day for full days, including lodging and meals, and $25/day for half days (meals only), with two people per trip;
for purposes of per diem, a 5-day week = 4.5 days, and a 4-day week = 3.5 days)

Year 1--assume 5 5-day weeks to collect 30 samples from Stratton field
        (5 x 400 miles) + (25 x 100 miles) + (2 x 5 x $265/trip per diem) = $2,430
        --1 4-day week to resample 8 wells in Stratton field once
        (1 x 400 miles) + (4 x 100 miles) + (2 x 1 x $205/trip per diem) = $630

Year 2--assume 2 5-day weeks to collect 10 samples from Stratton field
        (2 x 400 miles) + (10 x 100 miles) + (2 x 2 x $265/trip per diem) = $1,555
        --3 4-day weeks to resample 8 wells in Stratton field
        (3 x 400 miles) + (12 x 100 miles) + (2 x 3 x $205/trip per diem) = $1,890

2. Professional meetings:

4 meetings (1 in year 2, 3 in year 3) with airfare @ $500/trip, registration @ $150/trip, and per diem for 4 days/trip @ $80/day.

BUDGET

			YEAR 1	YEAR 2	YEAR 3	TOTAL
SALARIES						
A. Dutton Principal Investigator	1/1/1	man-months	4,940	5,138	5,343	15,421
R. Langford Research Associate	2/2/2	man-months	7,121	7,406	7,703	22,230
A. Fryar Research Associate	6/6/8	man-months	19,147	19,913	27,613	66,673
Unnamed Research Associate	3/3/3	man-months	9,900	10,296	10,708	30,904
Unnamed Graduate Research Assistants	6/6/6	man-months	12,500	12,875	13,261	38,636
Unnamed Support Staff			8,500	8,800	10,300	27,600
SUBTOTAL SALARIES			**62,108**	**64,428**	**74,928**	**201,464**
FRINGE BENEFITS & VSL 26.7% of salaries			**16,583**	**17,202**	**20,006**	**53,791**
MATERIALS AND SERVICES						
Expendable supplies			2,000	1,500	1,000	4,500
Rental for Portable Separator			9,500	8,500	0	18,000
Chemical and Isotopic Analyses			19,120	22,519	0	41,639
Thin Section Preparation			0	1,200	0	1,200
Publication Expenses			0	2,000	2,000	4,000
SUBTOTAL MATERIALS AND SERVICES			30,620	35,719	3,000	69,339
COMPUTER EXPENSES BEG Computer System			**10,000**	**10,000**	**15,000**	**35,000**
TRAVEL						
Sample Collection						
Mileage @ $0.275 per mile			1,500	1,113	0	2,613
Per Diem @ $80 per day			3,980	2,970	0	6,950
Presentation at Professional Meeting						
Airfare @ $600 each			0	600	1,800	2,400
Registration @ $150 each			0	150	450	600
Per Diem @ $100 per day			0	400	1,200	1,600
SUBTOTAL TRAVEL			**5,480**	**5,233**	**3,450**	**14,163**
EQUIPMENT						
Apple Macintosh IIsi			2,575	0	0	2,575
TOTAL DIRECT COSTS			**127,366**	**132,582**	**116,384**	**376,332**
INDIRECT COSTS			**61,148**	**64,965**	**57,028**	**183,141**
TOTAL COSTS			**188,514**	**197,547**	**173,412**	**559,473**