CONSOLIDATION OF GEOLOGIC STUDIES OF GEOPRESSURED-GEOTHERMAL RESOURCES IN TEXAS

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ABSTRACT

Hydrochemical data obtained from samples of brine produced from the Gladys McCall Zone 8 sandstone reservoir were used to estimate the importance of shale dewatering as a contribution to ultimate reservoir volume. Changes in chloride concentration of produced brines with time were generally small and close to analytical margins of error, but some correlation between production-related pressure drawdown and declining chlorinity was detected. More rigorous analysis of brine composition and source was hindered by nonstandardized sampling and analytical procedures. Geologic data suggest that sandstone interconnection is a more important source of extra reservoir volume than is shale dewatering at the Gladys McCall site. Methods for more definitively determining the affects of shale dewatering and reservoir interconnectedness include direct sampling and chemical analysis of shale water, pressure monitoring and fluid sampling in multiple reservoirs in a single well or a well field, and sidetrack drilling and coring.

Petrographic analysis was used to document the affects of experimental compaction on core samples from geopressured-geothermal reservoirs. Experimental compaction simulates the increasing effective stress within these reservoirs as fluid pressures decline during production. Inelastic compaction and brittle failure (fracturing) are closely related to sandstone composition. Sandstones that contain abundant ductile rock fragments and clay minerals undergo large compaction-induced porosity reductions and fracture readily at effective stress levels comparable to those generated in the reservoir during high-volume production. Well-indurated, high-quartz sandstones, such as the Gladys McCall Zone 8, are extremely resistant to both inelastic compaction and brittle failure.

ANALYSIS OF BRINE CHEMISTRY, GLADYS MCCALL TEST WELL

The Technadril-Fenix & Scisson Gladys McCall No. 1 geopressured-geothermal test well in Cameron Parish, Louisiana, underwent a series of production tests from 1983 through 1987 (Durrett, 1985; Riney, 1987). The most extensive Gulf Coast geopressured-geothermal test program to date, this project yielded much important data, especially in the areas of well producibility and operation. In this study we attempted to use the chemical compositions of brines produced from the Zone 8 reservoir to resolve some of the questions concerning fluid sources and recharge mechanisms that affect ultimate producible reservoir volume.

Reservoir Volume

Production and pressure data from 5 years of testing revealed the geopressured-geothermal reservoir at the Gladys McCall well site to be much larger than initially predicted. Although sparse subsurface data limited attempts to delineate the reservoir geologically, interconnection of a series of thick sandstones with the perforated Zone 8 Sandstone is probably the primary reason for the large reservoir volume. Other (probably minor) potential sources of extra pore volume are shale dewatering (Fowler, 1970; Riney, 1987), formation compaction and creep (Fahrenthold and Gray, 1985; Thompson and others, 1985), and leaking faults (Fowler, 1970).

Inadequate data precluded conclusive geologic determination of the physical dimensions and total pore volume of the Gladys McCall reservoir. Pyron (1981) estimated total pore volume to be 1.14×10^6 barrels (bbl) for six zones between 14,560 and 17,000 ft (4,440 and 5,180 m), but his data did not include logs from the test well. Bebout and Gutierrez (1983) constructed a detailed dip-oriented cross section (their fig. 61) that includes the electric log from the test well. From their cross section it is apparent that the massive (700 ft [210 m]) sandstone sequence that includes Zones 8 through 11 comprises a single, interconnected aquifer. Thin (<20 ft [6 m]) shale interbeds are not continuous across the fault block. Several small faults within the fault block offset but do not isolate the Zones 8 through 11 sequence. Unfortunately, deep well control is inadequate for mapping the sequence in three dimensions or for placing geologic constraints on boundary conditions. Numerical simulation of long-term reservoir performance (Pritchett and Riney, 1985; Riney, 1987) obtained a total pore volume of 2.5 x 10^9 bbl, using a conceptual model of thick sandstones separated by thin discontinuous shales. Assuming not only that the closely adjacent Zones 8 through 11 are interconnected but also that the more isolated Zones 1 through 7 also contribute, then total reservoir thickness would be 1,050 ft (320 m). Using the lateral dimensions (49,200 by 2,100 ft [15,000 by 640 m]) and average porosity (16 percent) of Riney (1987), total pore volume of Zones 1 through 11 would be 3.1 x 10^9 bbl. Similarly, total pore volume of Zones 8 through 11 alone would be 1.9 x 10^9 bbl. These are probably upper and lower limits of true reservoir volume and bracket the volume determined by Riney (1987) using numerical simulation. However, the boundary configuration cannot be geologically verified with the available subsurface data or uniquely determined with production and pressure data from one well.

Potential Recharge Mechanisms

Recharge of geopressured sandstone reservoirs by dewatering of adjacent, undercompacted shales would help to maintain reservoir pressure and production levels. The presence of low-salinity shale waters can be detected by a dilution of more saline reservoir fluids during production (Fowler, 1970). Accurate salinity (chlorinity) measurements during long periods of production should allow estimation of the volume of shale water being added to the reservoir. Shale-water salinity might be measured directly by perforating and producing shale horizons and accurately analyzing the composition of produced waters. These results can then be used to calculate the volume of shale water that must enter the reservoir to cause a given salinity decline. Dewatering gradients can be obtained by sidetrack coring. The water content of shale core samples can then be measured pyrolytically. Quantifying a decrease in water content of shales with proximity to the reservoir boundaries will indicate the total amount of dewatering.

Rock compaction and resulting pore-space reduction help to maintain fluid pressures in overpressured reservoirs (Thompson and others, 1985). The degree of rock compaction that has occurred in a reservoir during production can be directly measured by comparing changes in sandstone thickness and porosity before and after production, which requires a program of sidetrack coring. Thickness measurements obtained from cores and logs run in the sidetrack hole will allow estimation of the percentage of compaction and porosity reduction that the reservoir has undergone. Accurate directional surveys must be run in the sidetrack hole so that corrections can be made for deviation. Porosities and permeabilities of the sandstone in the sidetrack core can be compared with those of cores cut in the original hole prior to production testing. Experimentally compacted sandstones from the pre-production core can be compared with those in the sidetrack core to accurately estimate the type and degree of compaction. Shear fractures caused by increased effective stress during production-induced pressure drawdown may act as flow conduits to the wellbore and could explain the relatively high permeability of some geopressured sandstones after extended production.

It would be difficult to accurately determine the volume of water added to a geopressured reservoir by leaking faults. Brines leaking into reservoirs along fault planes from adjacent fault blocks may be detected by slight increases in the salinity of produced waters (Fowler, 1970), but these increases would not be discernible in the relatively short production tests conducted in geopressured-geothermal test wells. Distinctive chemical or isotopic compositions may be useful for detection and source determination of brines introduced into the reservoir through leaky fault zones.

Limitations of Chlorinity Measurement

Annual changes in chlorinity are close to analytical margins of error, so that results from limited (1 or 2 yr) geopressured-geothermal tests may not be scientifically meaningful. The problem is complicated by nonstandardized analytical techniques in the laboratory and by imprecise field measurements. Standard laboratory methods of measuring the chloride content of formation waters have relative standard deviations (coefficient of variation) of 1.7 percent (S. W. Tweedy, personal communication, 1986). Analyses of chloride contents of brines using the field kit designed by researchers at Rice University have a precision of 2 to 5 percent (M. B. Tomson, personal communication, 1986).

Fowler (1970) calculated percentage change in chloride concentration over a 28-yr period using 94 water analyses from Frio reservoirs in the Chocolate Bayou and Chocolate Bayou West fields, Brazoria County, Texas (table 1). Mean annual declines in chlorinity ranged from 0.02 to 4.01 percent, averaging 1.48 percent for all reservoirs. Fowler (1970) concluded that the pattern of decreasing salinity with time resulted from dilution of original formation waters by fresher shale waters. Three Chocolate Bayou reservoirs showed slight increases in chloride content, ranging from 0.03 to 0.09 percent/yr, which may have resulted from water encroachment along faults from more saline aquifers (Fowler, 1970).

Chlorinity analyses of production waters from the geopressured-geothermal test wells span a much shorter time than that encompassed by Fowler's (1970) data. The Andrau (C Zone) reservoir at the Pleasant Bayou No. 2 test well in Brazoria County, Texas, produced greater than 3.5 million barrels (Mmbbl) during a 6-month production test in 1982 and 1983. Prior to this test, a chloride concentration of 79,000 mg/L was reported (Rodgers, 1983), whereas a post-test analysis yielded 75,200 mg/L chloride (Sloan, 1983). Assuming this chlorinity decrease resulted from shale dewatering that occurred during the 6-month production test, then an apparent 9.6 percent annual decline is obtained, which is much larger than long-term declines in nearby Chocolate Bayou reservoirs (table 1). However, brine-production rates are probably much higher in the Pleasant Bayou

Table 1. Historical salinity variations in Chocolate Bayou and Chocolate Bayou West fields, Brazoria County, Texas (Fowler, 1970).

Reservoir	Sampling Dates		Chloride Change (%) Cumulative	Annual
Chocolate Bayou				
Frio A	5/46	12/64	-12.4	-0.67
Alibel	12/56	3/68	-33.0	-2.93
U. Houston Fms.	6/42	4/68	+2.3	+0.09
L. Houston Fms.	12/56	11/64	-31.8	-4.01
Rycade	10/56	12/64	-28.0	-3.44
Banfield	4/52	12/64	-16.6	-1.32
U. Weiting	12/64	4/68	-6.3	-1.62
L. Weiting	12/64	3/68	-8.5	-2.59
S	12/56	4/68	+0.8	+0.07
Chocolate Bayou West				
Frio A	9/46	4/68	-6.0	-0.28
Frio B	6/46	4/68	-0.5	-0.02
Frio C	7/47	4/68	+0.7	+0.03
Andrau	5/40	12/56	-42.3	-2.57

test well than they are in oil and gas wells, and, theoretically, higher rates of production and pressure drawdown should accelerate shale dewatering. The Zone 8 Sandstone at the Gladys McCall test well produced about 18 Mmbbl between January 1984 and September 1986 (1.5 yr). During this production period, chloride concentrations declined from 59,290 to 57,700 mg/L (Randolph, 1986), obtaining a mean annual decline of 1.8 percent, which is comparable with the long-term data from the Chocolate Bayou reservoirs (table 1). Analytical uncertainty, however, limits the value of these data for estimating the volumes of shale water that enter geopressured reservoirs during production. Standardized analytical techniques and carefully controlled conditions at one laboratory might reduce analytical uncertainty enough to allow detection of small salinity declines in waters from short-term, high-flow production tests.

Pressure Drawdown and Chloride Decline

Some data suggest chlorinity declines are related to shale dewatering that was induced by pressure drawdown in the Gladys McCall well. Laboratory measurements of the chloride content of formation waters from the Zone 8 Sandstone (table 2) were plotted against the calculated bottom-hole pressures in the Gladys McCall well for the production period from the 4th quarter, 1983 to the 1st quarter, 1986 (fig. 1). During this period trends of chloride decline parallel average rates of bottom-hole pressure decline (fig. 1). Undercompacted shales in a geopressured sequence are saturated with low-salinity fluids. Production-induced fluid-pressure drawdown in the adjacent sandstones increases effective stress, accelerates shale compaction, and creates hydrodynamic potential for flow from the shales into the sandstone reservoirs. This process appears to be rate sensitive, greater drawdowns resulting in larger influx of shale waters (fig. 1). Bottom-hole pressures and salinities of produced waters both increased after the Gladys McCall well was temporarily shut-in in late 1984 for treatment of tubing scaling (fig. 1).

The correlation between pressure and salinity variations may be attributed to the accumulation of a layer of shale water along the upper boundary of the Zone 8 Sandstone (fig. 2). During

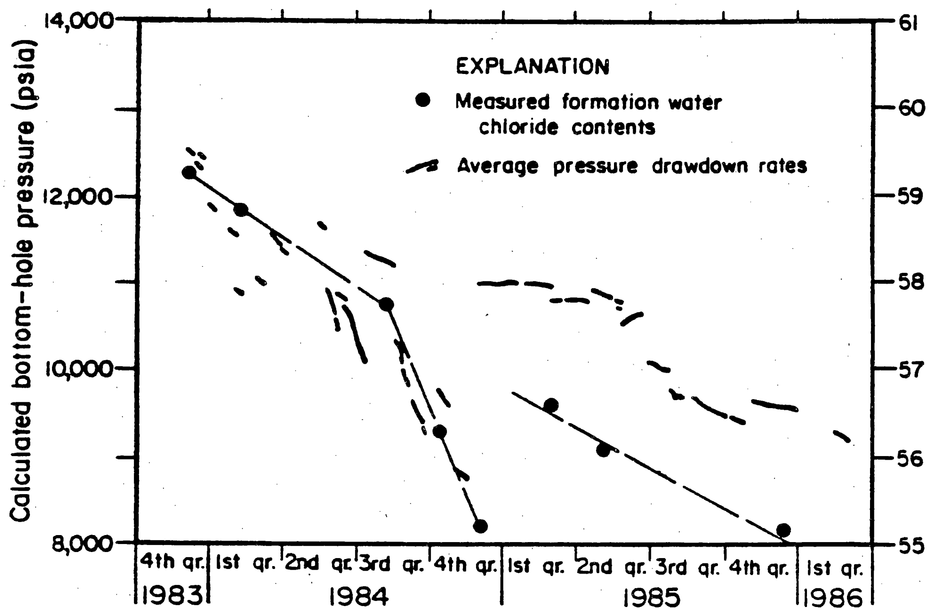

Figure 1. Calculated bottom-hole pressures and chloride concentrations of formation waters produced from the Zone 8 reservoir in the Gladys McCall test well. Pressure data from Randolph (1986). Formation water chloride contents from table 2.

Table 2. Chloride content of Zone 8 production waters, Gladys McCall test well.

Sampling Date	Chloride (mg/L)	Laboratory
11/83	59,290	Rice University
2/84	58,700	IGT
8/84	57,750	IGT
10/84	56,300	IGT
12/84	55,200	IGT
2/85	56,600	IGT
5/85	56,100	IGT
12/85	55,200	IGT
9/86	57,700	Bureau of Economic Geology
12/86	57,367	Rice University

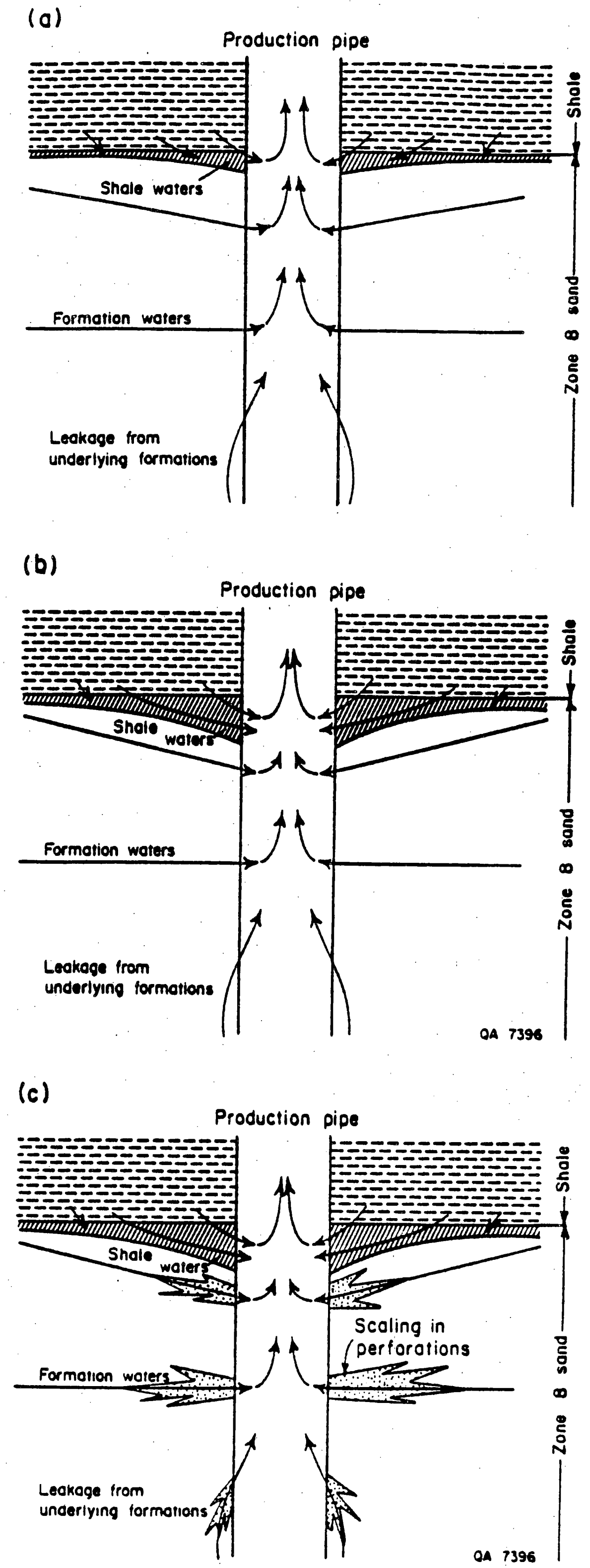

Figure 2. Diagrams of hypothetical shale-water flow patterns near the wellbore at (a) low rate of pressure drawdown, (b) high rate of pressure drawdown, and (c) during the development of scaling.

production the low-salinity shale water could move laterally along this boundary without appreciably mixing with denser brines in the sandstone and enter the wellbore through the uppermost perforations. When production and pressure drawdown are relatively low, the shale-water layer would be thin and would contribute less to total production (fig. 2a), but when production and drawdown rates are high, a thicker shale-water layer would contribute more to total production (fig. 2b). When the well is shut-in, fluid pressure buildup in the reservoir would inhibit further shale dewatering, and in the absence of flow toward the wellbore, reservoir brine would mix with and disperse the shale-water layer. Thus, if this hypothesis is correct, salinity should increase after well shut-in periods. By selectively isolating perforations at various levels in the Zone 8 Sandstone, it might be possible to detect vertical salinity gradients or the presence of a shale-water layer.

Scaling (mineral precipitation blocking perforations) was responsible for the large decline in calculated bottom-hole pressures that occurred in late 1984 (Randolph and Osif, 1986) (fig. 1). If scaling developed preferentially below the postulated shale-water layer (fig. 2c), owing to the high calcite saturation level of the reservoir brine, then the proportion of shale water produced would increase, decreasing measured salinities. Reduced shale dewatering and thus increased salinity of produced brine would be expected once scale was removed.

Analysis of Chemical Compositions of Produced Brines

Changes in the concentrations of dissolved constituents in brines produced from the Gladys McCall test well either may reflect important reactions occurring in the reservoir or may be the result of sampling and analytical procedures. Unfortunately, we were unable to resolve this question satisfactorily. As with chlorinity, many of these changes were near the limits of analytical resolution, and this problem was compounded by nonstandardized procedures among the laboratories that analyzed brine samples. One example, involving changes in alkalinity (expressed as bicarbonate concentration) and barium concentration, is discussed on page 12.

The alkalinity of Gladys McCall Zone 8 brines apparently increased after treatment of the well for carbonate scaling in June 1985 (table 3). Randolph and Osif (1986) assumed that the change was related to the chemicals (dominantly phosphonates) injected into the reservoir to inhibit scale precipitation. Assuming equilibrium between calcite and dissolved carbonate under reservoir conditions, we calculated the mole percent of carbon dioxide that would occur in the exsolved gas phase at the surface. Using the bicarbonate concentration reported by IGT (488 mg/L), calculated carbon dioxide coincided with surface measurements, whereas carbon dioxide calculated with the bicarbonate concentration reported by SCAN (285 mg/L) fell far short of measured values. During numerous field analyses of Zone 8 brines in March 1985, Tomson (1986) obtained bicarbonate concentrations (430 to 500 mg/L) that support the IGT analysis. Thus, the anomalously low value reported by SCAN may have resulted from carbonate precipitation in the sample container prior to laboratory analysis. Their low barium concentration (table 3) may also be due to precipitation.

Rigorous and standardized guidelines for sampling, storing, and analyzing reservoir fluids from geopressured-geothermal test wells would greatly increases the value and scientific validity of results, enabling more definitive interpretations and conclusions. We suggest following the procedures outlined by Lico and others (1982).

METHODS FOR TESTING GEOPRESSURED-GEOTHERMAL WELLS

As the Gulf Coast geopressured-geothermal energy program enters advanced stages of development, test procedures must be designed to obtain the types of data necessary for initiation of commercial development of the resource. These data should help answer questions concerning long-term reservoir behavior, well performance, and commercial value of produced fluids. Potential for development of multiple-well fields should also be considered and tested. In this section, several test procedures will be discussed for addressing shale dewatering and reservoir interconnectedness, continuity, and internal heterogeneity. Methods for rigorous analysis and interpretation of the chemical compositions of produced fluids (including hydrocarbons) and

Table 3. Chemical compositions of Gladys McCall, Zone 8 brines used to calculate the amount of carbon dioxide gas exsolved during production.

Sample date	10/12/84	12/17/85
Laboratory	SCAN	IGT
Analytical results (mg/L):		
Alkalinity	285	488
Barium	44	576
Calcium	3,840	3,900
Chloride	56,300	55,200
Potassium	41	788
Magnesium	348	280
Sodium	33,900	34,000
pH (standard units)	6.2	6.8
Temperature (oC)	147	159
Mole % CO_2 in gas	9.9	9.9

compositional changes through time, although not discussed in this report, are currently being developed at the Bureau of Economic Geology.

Production of Shale Water

To determine the extent of shale dewatering during production, the chemical composition of shale water must be measured directly. Several test procedures might accomplish this. If a cone of shale water develops during pressure drawdown around the well bore and along the upper boundary of the reservoir (fig. 2), direct sampling could be accomplished by preferentially producing fluids from this cone. It might be possible to isolate the upper few feet of perforations with a packer in such a way that high rates of production from the rest of the reservoir could be continued through the central tubing while fluids from the upper few feet are drawn up through the annulus. If shale dewatering is significant, the fluids produced through the annulus will be derived mainly from shales overlying the reservoir. Chemical analysis of these fluids will give at least an approximation of shale-water composition.

Shale water might also be collected by perforating a shale zone and attempting to produce it. However, low shale permeability would be a problem, severely limiting production volumes. Successful collection entails waiting until the tubing adjacent to the perforated shale fills with fluid and then retrieving some of that fluid with a Schlumberger-type down-hole fluid sampler (H. Dunlap, personal communication, 1987). If shale-water samples can be collected using this method, accurate measurements of fluid composition and of in situ temperature, pressure, and pH are possible.

Testing of Multiple Reservoirs

In interbedded sandstone and shale sequences, sandstone reservoirs are commonly interconnected because of fault displacement and lateral shale pinch-out. The degree of sandstone interconnectedness bears directly upon ultimate reservoir volume and long-term producibility of a geopressured-geothermal well. Conducting pressure and flow tests in several reservoirs in a single well would provide information about sandstone interconnectedness. Each reservoir is perforated, flow tested, and then shut-in. Pressures are measured during both the flowing and the shut-in phases. The sequence of testing can be designed to enable the detection of pressure drawdown in one reservoir that is caused by production in an adjacent, interconnected reservoir. Comparison of fluid compositions among the reservoirs can also yield clues about relative interconnectedness.

A second method for testing reservoir continuity involves monitoring pressures in several different wells while producing the test well. Accomplishing this without drilling additional test wells requires the existence of nearby commercial gas wells that produce from either the test reservoir or closely adjacent reservoirs. The Railroad Commission of Texas requires gas well operators to report production and bottom-hole pressure data semiannually for every producing well. Monitoring production and pressure trends in the appropriate gas wells during long-term geopressured-geothermal production testing allows more definitive reservoir modeling and simulation than does obtaining data from a single well.

Sidetrack Drilling

Following long-term production testing, drilling several sidetrack holes in a geopressured-geothermal well will provide data on post-production changes in the reservoir that extend a few feet to tens of feet away from the original hole. This sidetracking program will also enable the study of lateral geologic heterogeneities in the reservoir that are much smaller than what can be delected with typical well spacing. Sidetrack holes will be geophysically logged, and selected zones will be cored. Cores will be examined for evidence of reservoir compaction and shale dewatering induced by pressure drawdown, and for chemical alterations caused by the scale inhibitor. Using both cores and logs, detailed correlations can be made to trace lateral stratigraphic continuities and changes that affect local fluid flow patterns. Thus, a sidetracking program is an excellent culmination of geopressured-geothermal well testing, allowing final reservoir evaluation that could lead to improvement of techniques and procedures used in succeeding tests or commercial ventures, in addition to providing data for small-scale geologic investigations that could lead to better understanding of reservoir complexity.

PETROGRAPHIC STUDIES OF CORE SAMPLES USED IN ROCK MECHANICS EXPERIMENTS

Petrographic analysis of geopressured-geothermal sandstone reservoirs complements experimental studies on the mechanical properties of these sandstones conducted by the Center for Earth Sciences and Engineering, The University of Texas at Austin (Gray and others, 1980; Jogi and others, 1981; Thompson and others, 1980, 1981, 1985; Fahrenthold and Gray, 1985, 1986a, 1986b). In these studies, core samples were experimentally compacted to simulate the increasing effective stress that develops in the reservoir during high-volume production and fluid-pressure drawdown. We conducted mesoscopic and microscopic examinations of both uncompacted and experimentally compacted core samples. This report includes petrographic descriptions of quartz-rich Zone 8 sandstone from the Gladys McCall test well and Frio A sandstone reservoir from the Hitchcock Northeast gas field in Galveston County, Texas. In the Frio A sandstone, durable quartz is less abundant and more ductile rock fragments are common. The effects of experimentally induced, elastic deformation and brittle failure on these different types of sandstone are discussed. Results are compared with published data from the Andrau (C Zone) reservoir in the Pleasant Bayou test wells (Gray and others, 1980; Loucks and others, 1980; Jogi and others, 1981), which is compositionally intermediate between the Zone 8 and Frio A sandstones. Finally, the implications of potential production-induced compaction on the reservoir performance of sandstones of various compositions are considered.

Frio A Sandstone, Hitchcock Northeast Field

Frio A sandstone petrography was studied using core samples and thin sections from 9,156 to 9,189.5 ft (2,791 to 2,802 m) in the Secondary Gas Recovery, Inc., Delee No. 1 well (Light, 1987). Using the point-counting method, we estimated mineral composition and porosity (table 4). The Frio A sandstone is a fine- to medium-grained, poorly sorted, feldspathic litharenite (fig. 3); porosity averages 18 percent. Quartz, feldspar, chert, volcanic rock fragments, and chlorite clasts are the main sand-sized framework constituents. Corroded, partly dissolved feldspars compose about 2 percent of the framework. Carbonates, kaolinite, chlorite, and quartz occur as pore-filling cements. In the Frio A sandstone, porosity increases with increasing quartz content (fig. 3). The abundance of durable quartz grains in sandstone is a function of source-rock composition and textural maturity. Maturity is a measure of the degree of sediment winnowing and reworking before final deposition. Winnowing and reworking increase grain sorting and rounding and eliminate less durable minerals. Thus, textural maturity is generally proportional to primary porosity and quartz content. In deeply buried Frio sandstones, the correlation between porosity and quartz content is enhanced by secondary (postdepositional) dissolution of feldspar and volcanic rock fragments. Depositional facies, petrography, and diagenesis of the Frio A sandstone are described in greater detail by Light (1987).

Extension and shear fractures inclined 16° and 45° to the direction of maximum stress formed in the Frio A sandstone during experimental compaction. In these experiments, the direction of maximum stress always coincided with the long axes of vertically oriented core samples. These fractures commonly occur in parallel and en echelon, crosscutting systems. Irregular, horizontal and vertical expansion fractures developed during postcompaction decompression of the cores. This continuous, roughly orthogonal network of fractures may provide pathways for fluid flow, even though microscopic examination revealed that intergranular permeability is reduced during compaction.

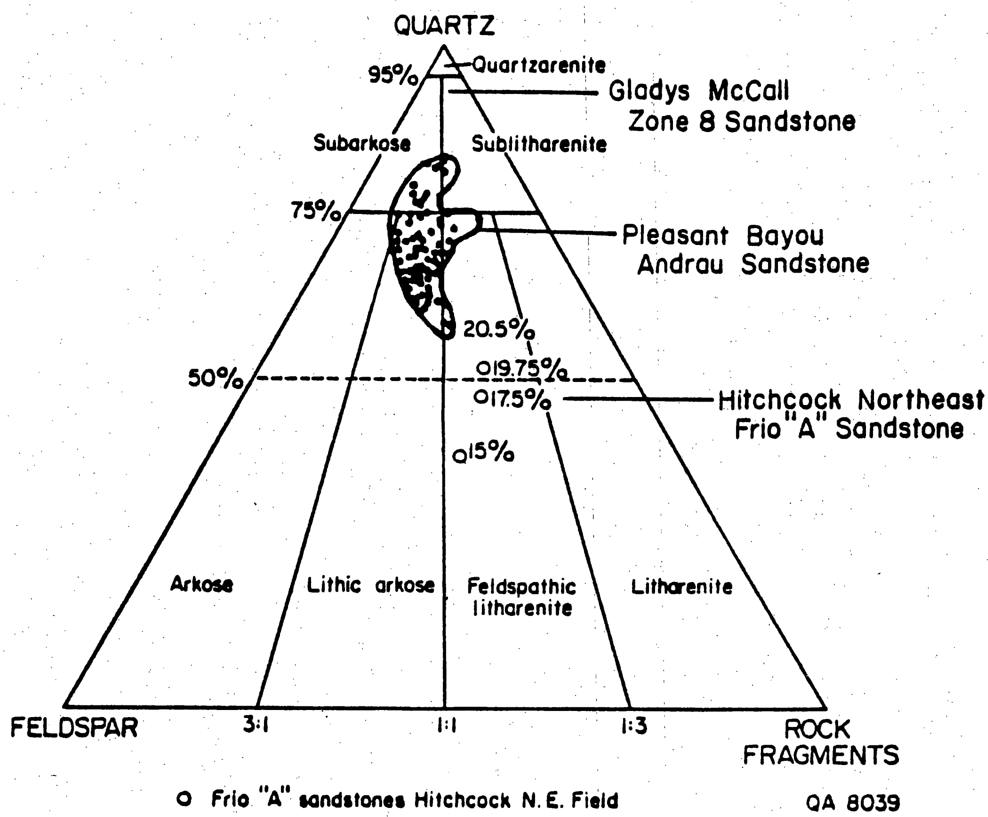

Figure 3. Compositions of sandstone core samples from the Gladys McCall and Pleasant Bayou geopressured-geothermal test wells and the Delee No. 1 co-production test well in Hitchcock Northeast field. Porosities are given by each Hitchcock Northeast data point. Sandstone classification after Folk (1974).

Table 4. Relative percentages of framework grains and porosity from thin section point counting.

Depth (ft)	Quartz	Feldspars	Rock Fragments	Porosity
Frio A sandstone, Delee No. 1 well				
9,156.0	38.3	29.5	32.2	15.0
9,166.0	59.9	18.2	21.9	20.5
9,177.5	47.2	21.9	30.9	17.5
9,189.5	52.2	18.3	29.5	19.8
Averages	49.4	22.0	28.6	18.2
Zone 8 sandstone, Gladys McCall No. 1 well				
15,354.3	83.1	7.6	9.3	13.0
15,355.0	86.2	5.4	8.4	14.5
15,356.0	91.2	4.4	4.4	8.0
15,356.5	87.8	8.3	5.0	10.0
15,357.8	85.8	4.1	10.1	13.0
15,358.0	83.1	5.2	11.6	12.0
15,374.8	87.2	3.3	9.4	9.5
Averages	86.3	5.5	8.3	11.4
Andrau sandstone, Pleasant Bayou No. 2 well				
14,685.0	77.0	12.1	10.9	1.0
14,687.0	55.2	22.4	22.4	11.4
14,689.0	64.2	21.8	13.9	11.8
14,691.0	65.4	19.0	15.6	13.3
14,693.0	60.3	25.5	14.1	10.1
14,695.0	57.9	25.7	16.4	11.2
14,697.0	67.7	18.0	14.4	15.0
14,699.0	74.5	18.8	6.7	20.0
14,701.0	54.4	30.4	15.2	7.6
14,703.0	45.9	24.6	29.2	2.5
14,705.0	64.2	20.7	15.1	19.3
14,707.0	59.0	25.5	15.5	17.9
14,709.0	70.2	20.9	8.9	20.5
14,711.0	60.8	21.6	17.6	18.8
14,713.0	64.0	22.8	13.2	12.9
14,715.0	70.2	20.2	9.5	17.5
Averages	63.2	21.9	14.9	13.2

The effects of experimental compaction on porosity and permeability in the Frio A sandstone were documented microscopically by point-counting vertically oriented (perpendicular to bedding), rock thin sections. The petrographic point-counting method generally identifies only effective (interconnected) porosity (macroporosity), which is closely related to permeability (Loucks and others, 1980). Conventional (porosimeter) measurements in core plugs quantify total porosity, part of which is essentially isolated from permeable flow (microporosity). Thus, the porosities listed here are somewhat lower than the conventional porosities generally associated with these reservoirs.

In experimentally compacted samples of the Frio A sandstone, effective porosity reduction is inversely proportional to quartz content. Out of a total porosity reduction of 42 to 62 percent, as much as 7 to 10 percent may be attributable to collapse of partly dissolved (vacuolized) feldspars, whereas the rest resulted from deformation of ductile grains (volcanic rock fragments and clay clasts). Deformation of ductile grains and intergranular cements allow more durable quartz and feldspar grains to rotate and move into pores. In more quartz-rich samples, crosscutting fracture networks appear microscopically as 3- to 5-mm wide zones where precompaction porosity is largely preserved. Where ductile grains are more abundant, porosity loss is more homogeneous, and fracture porosity is less well developed.

Zone 8 Sandstone, Gladys McCall Test Well

Core samples and thin sections from 15,354 to 15,375 ft (4,681 to 4,688 m) in the Gladys McCall geopressured-geothermal test well were used for petrographic characterization of the Zone 8 sandstone. It is a fine- to medium-grained, well-sorted, well-rounded, quartz-rich sublitharenite to subarkose (fig. 3). Point-count porosity averages 11.2 percent (table 4). Feldspars are subordinate components of the sand framework (less than 10 percent, table 4). Detrital clay (sericite and kaolinite), organic material, and shell fragments occur locally. Open pores up to 0.25 mm across have resulted from secondary dissolution of framework grains (dominantly feldspars). Quartz overgrowths are the most abundant pore-filling cement. Pressure-solution boundaries (stylolites) between grains are common, and along with the quartz overgrowths, form a tightly interlocking rock fabric. Pressure solution of quartz may be the source of some of the silica in the grain overgrowths. Minor cementation by illite, chlorite, and kaolinite occurred after the formation of quartz overgrowths. Kaolinite also replaces some feldspar grains.

The Zone 8 sandstone core samples were extremely resistant to fracturing (brittle failure) during experimental compaction. High rock strength can be attributed to well-developed quartz overgrowths and interlocking grain boundaries. Inelastic compaction caused by deformation of ductile grains and rotation of quartz grains did not occur during experimental compaction. High quartz content and stylolitic grain contacts prevented deformation and rotation prior to brittle failure.

Brittle failure of Zone 8 sandstone did occur at very high effective stress levels and exhibited a variety of forms. Some quartz grains fractured conchoidally without destroying grain shapes or overall framework texture of the sandstone, whereas others shattered completely (granulation), forming a whitish, opaque rock flour (finely granulated quartz). With the aid of a binocular microscope, this texture was clearly visible both on the surfaces of shear fractures and as random patches in unfractured areas. Random distribution of crushed quartz grains suggests that stress was evenly distributed throughout the rock during experimental compaction. Anastomosing shear fractures cut both around and through quartz grains. Curved shear fractures range from 45° to 14° relative to the direction of maximum compression (vertical core axis). Conical fractures formed at the ends of some core samples. Sets of conjugate shear fractures formed that are oriented 25° to 31° to the direction of maximum stress. Irregular vertical extension fractures also formed. Where a bedding plane separates zones of medium and fine-grained sandstone, a steeply dipping shear fracture curves and converges with this prominent bedding plane. Another irregular shear, subparallel to the bedding plane, terminates at the more steeply dipping shear, indicating that the steep shear formed last.

High in situ pressures and temperatures in the geopressured-geothermal interval at the Gladys McCall test well site have caused incipient metamorphic recrystallization. The Zone 8 sandstone has a crude ribbon texture subparallel to bedding within which quartz grains show interpenetrating contacts owing to pressure solution. Suturing has locked grains together and produced a metaquartzite-like fabric that is resistant to inelastic deformation. Thus, no detectable porosity reduction occurred prior to brittle failure.

Andrau Sandstone, Pleasant Bayou Test Well

The Andrau (C Zone) geopressured-geothermal reservoir at Pleasant Bayou exhibits a compositional range that spans the difference between the Gladys McCall Zone 8 sandstone and the Hitchcock Northeast Frio A sandstone. Samples from the cored part of the Andrau sandstone (14,685 to 14,715 ft [4,477 to 4,486 m]) are typically fine- to medium-grained, well-sorted subarkoses and lithic arkoses (fig. 3). Point-count porosity averages 13.2 percent (table 4). Quartz grains comprise 46 to 77 percent (63 percent mean) of the sand framework in the Andrau, 38 to 60 percent (49 percent mean) in the Frio A, and 83 to 91 percent (86 percent mean) in the Zone 8 (table 4). The rest of the sand framework in the Andrau sandstone consists largely of feldspar and volcanic rock fragments. Minor detrital clay, micas, heavy minerals, shell fragments, and organic debris are also present (Loucks and others, 1980). Quartz overgrowths, kaolinite, and minor carbonate occur as intergranular cements (Loucks and others, 1980).

Although samples of experimentally compacted Andrau sandstone were not examined petrographically, measurements made in the rock mechanics laboratory (Gray and others, 1980; Jogi and others, 1981) indicate that this Pleasant Bayou reservoir sandstone is generally more resistant to compaction than the Frio A sandstone but less resistant than the Zone 8 sandstone. Ductile deformation (inelastic compaction) resulted in 6 to 8 percent porosity reduction in the Andrau sandstone, 42 to 62 percent porosity reduction in the Frio A sandstone, but essentially zero porosity reduction in the Zone 8 sandstone. Core samples of the Andrau sandstone were subjected to effective stresses of as much as 15,000 psi before brittle failure occurred and shear fractures developed. Frio A sandstone samples failed at effective stresses of 3,000 to 4,000 psi, whereas

Zone 8 sandstone samples did not fail until effective stresses reached 75,000 psi (E. Fahrenthold, personal communication, 1987).

Implications

In geopressured-geothermal reservoirs, high-volume production reduces in situ fluid pressures, thus increasing effective stress and potentially resulting in reservoir compaction. Deformation of less durable grains and rotation of harder grains (dominantly quartz) occlude porosity, especially near the wellbore, where pressure gradients are greatest. This type of deformation (inelastic compaction) can inhibit flow and reduce production. Based on porosity reductions observed petrographically (Zone 8 and Frio A) or measured mechanically (Andrau), post-compaction effective porosities average 8.7 percent in the Frio A (52 percent mean reduction), 12.3 percent in the Andrau (7 percent mean reduction), and 11.4 percent in the Zone 8 (0 percent reduction). The Frio A sandstone has the highest initial porosities, and this mineralogically heterogeneous reservoir also has the greatest potential for production-induced destruction of intergranular porosity. The Zone 8, a well-cemented and well-indurated, quartz-rich sandstone, will not compact as production reduces fluid pressures, and so reservoir performance should not suffer from inhibition of fluid flow to the wellbore. Only minor compaction should occur in the Andrau resevoir at Pleasant Bayou.

At high effective stresses, brittle failure occurs and shear fractures form. Experimentally-induced brittle failure enhanced porosity in the Frio A sandstone through the development of a network of fracture porosity. Additionally, Frio A core samples failed at effective stress levels, which could be created by sustained high-volume production. However, overburden and confining pressures in the reservoir environment might reseal any fractures that form. Thus, it is unknown how shear fracturing affects geopressured reservoir performance. Both the Andrau and Zone 8 sandstones are probably too well-indurated to fracture at the levels of effective stress that would be created during fluid-pressure drawdown.

Compositional variations within the Andrau Sandstone at Pleasant Bayou will affect how this reservoir responds to production-induced increases in effective stress. Parts of the reservoir that are rich in volcanic rock fragments and clay may deform and develop shear fractures. In the Andrau, mineralogically immature sandstone (low quartz relative to rock fragments and clay) occurs mainly in interbedded sandstone/shale zones that flank the main massive sandstone sequence. Production perforations are in the central massive (70-ft- [20 m-] thick) zone, which is relatively more mature mineralogically (higher quartz). Additionally, Thompson and others (1980, 1981, 1985) have measured pronounced time-dependent deformation (creep) in sandy shale core samples from the Pleasant Bayou test wells. Compaction along the margins of the Andrau reservoir and in enclosing shales and sandy shales may contribute to shale dewatering.

CONCLUSIONS

Although much of the geologic and hydrochemical data from the Gladys McCall test well are limited or ambiguous, the large volume of the Zone 8 reservoir is probably due primarily to permeable interconnections among several thick sandstones in Zones 1 through 11. Analysis of the chemical compositions of produced brines to estimate the extent of shale dewatering was inconclusive. Because Zones 8 through 11 are dominated by thick sandstones with thin shale interbeds, total shale volume may be inadequate for dewatering to make a significant contribution to reservoir fluid volume. Results of experimental compaction studies suggest that the well-indurated, high-quartz Zone 8 sandstone resists formation compaction during fluid-pressure drawdown. Thus, compaction-induced porosity reduction is minimal, but so is compaction-related pressure maintenance. Porosity reduction near the wellbore would inhibit inward flow, but more general reservoir compaction can increase production volume for a given amount of pressure decline. Structural influences on reservoir volume, specifically leaky faults, could not be determined. The experience at the Gladys McCall test well indicates new or improved testing, sampling, and analytical procedures that would provide high-quality data are needed to determine long-term reservoir behavior, ultimate producible volume, and fluid sources and compositions in geopressured-geothermal systems.

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