Capillary Sealing as an Overpressure Mechanism in the Anadarko Basin*

By

Constantin Cranganu[1] and Maria A. Villa[1]

Search and Discovery Article #40187 (2006)
Posted March 14, 2006

*Modified from extended abstract prepared for presentation at AAPG Annual Convention, Calgary, Alberta, June 19-22, 2005

[1]Brooklyn College, Brooklyn, NY (cranganu@brooklyn.cuny.edu)

Abstract

The Anadarko Basin in southwestern Oklahoma is known to contain today areas of extensive overpressures (pressures higher than hydrostatic pressure). Explaining the origin and maintenance of overpressured pore-fluids in the basin over long periods of time cannot be achieved by invoking classical, common causes, such as compaction disequilibrium or gas generation. We propose a capillary sealing mechanism that is responsible for both generating and maintaining almost all overpressure observed today in the Anadarko Basin. Capillary sealing occurs in a sedimentary basin when capillary forces act at gas-water interfaces between coarse- and fine-grained clastic rocks. Detecting capillary seals and estimating the magnitude of their pressure sealing implies two main aspects: (1) measuring the pore throat radius of coarse- and fined-grained clastic rocks, and (2) detecting the presence of gas-bearing layers using geophysical logs and other data. Measurements by injecting mercury into rock pores allow estimation of the pore throat radii controlling the capillary sealing. 21 fine-grained rock samples from the Anadarko Basin were thus measured and the average pore throat radius was found to be 2.5×10^{-8} m. The proposed model also requires the presence of gas-bearing layers interbedded into shale layers. Using a suite of geophysical logs from more than 100 wells, we were able to identify such gas-saturated layers in more than 50 wells. Further calculation indicates that a capillary sealing mechanism in the overpressured area of the Anadarko Basin may produce ~40 MPa of pressure, or ~80% of the maximum observed overpressure in the basin.

Introduction

Many sedimentary basins throughout the world experience fluid pressures above or below the normal (i.e., hydrostatic) pressure (Fertl, 1976; Hunt, 1990; Bigelow, 1994). The common name for these situations is “abnormal high- or low-pressure”, “geopressure”, “overpressure” (above the hydrostatic) or “underpressure” (below the hydrostatic pressure value).

More common than the “underpressure”, the “overpressure” situation occurs in a sedimentary basin due to one or more of the following causes (Osborne and Swarbrick, 1997) (1) increase of compressive stress, (2) change in the volume of the pore fluid or rock matrix, and (3) fluid movement or buoyancy. A fast subsidence process can generate considerable overpressure due to increase loading during sediment burial, especially when sediments have low permeability and fluids cannot be expelled from buried sediments at the same rate as the subsidence rate. Gas generation could possibly produce overpressure, depending upon the type or organic matter (kerogen) implied in the process, temperature history of the sedimentary basin, abundance of organic matter, etc.

Overpressure in the Anadarko Basin, Oklahoma

The Anadarko Basin in southwestern Oklahoma (Figure 1) is known to contain today areas of extensive overpressure (Hunt, 1990; Jorgensen, 1989; Jorgensen et al., 1993; Al-Shaieb et al., 1992; Al- Shaieb et al., 1994, 1994b). Al-Shaieb et al. 1992, 1994a, 1994b, stated that fluid pressures exceeding hydrostatic pressure generally start at ~2.3 to 3.0 km depth, but return to near-hydrostatic pressure value below the Woodford Shale. They also hypothesized about the presence, within overpressure zone, of three different levels of compartmentalization, such that overpressurized fluids are not ubiquitous present in the basin, but confined to distinct compartments.

Explaining the origin of overpressure regime and its maintenance over long periods of time in the basin is not a simple task if one tries to apply the classical concepts (disequilibrium compaction or gas generation). The Anadarko Basin has not experienced significant sedimentation for more than 200 million years, and has undergone uplift and erosion for ~100 million years (Gilbert, 1992). Consequently, one cannot invoke compaction disequilibrium as a possible mechanism for overpressure regime in the Anadarko Basin, unless a pressure seal, capable of maintaining overpressure for millions of years, is invoked. Analyzing this hypothesis, Lee and Deming (2002) considered that the presentday overpressures in the Anadarko Basin were remnant of Paleozoic compaction disequilibrium preserved for about 250 million years. They found out that the process of preserving overpressures for such period of time would require a pressure seal 100 m thick with a permeability lower than 10^{-27} m^2. This permeability is many orders of magnitude lower than the lowest rock permeabilities ever measured (Neuzil, 1994, 1995).

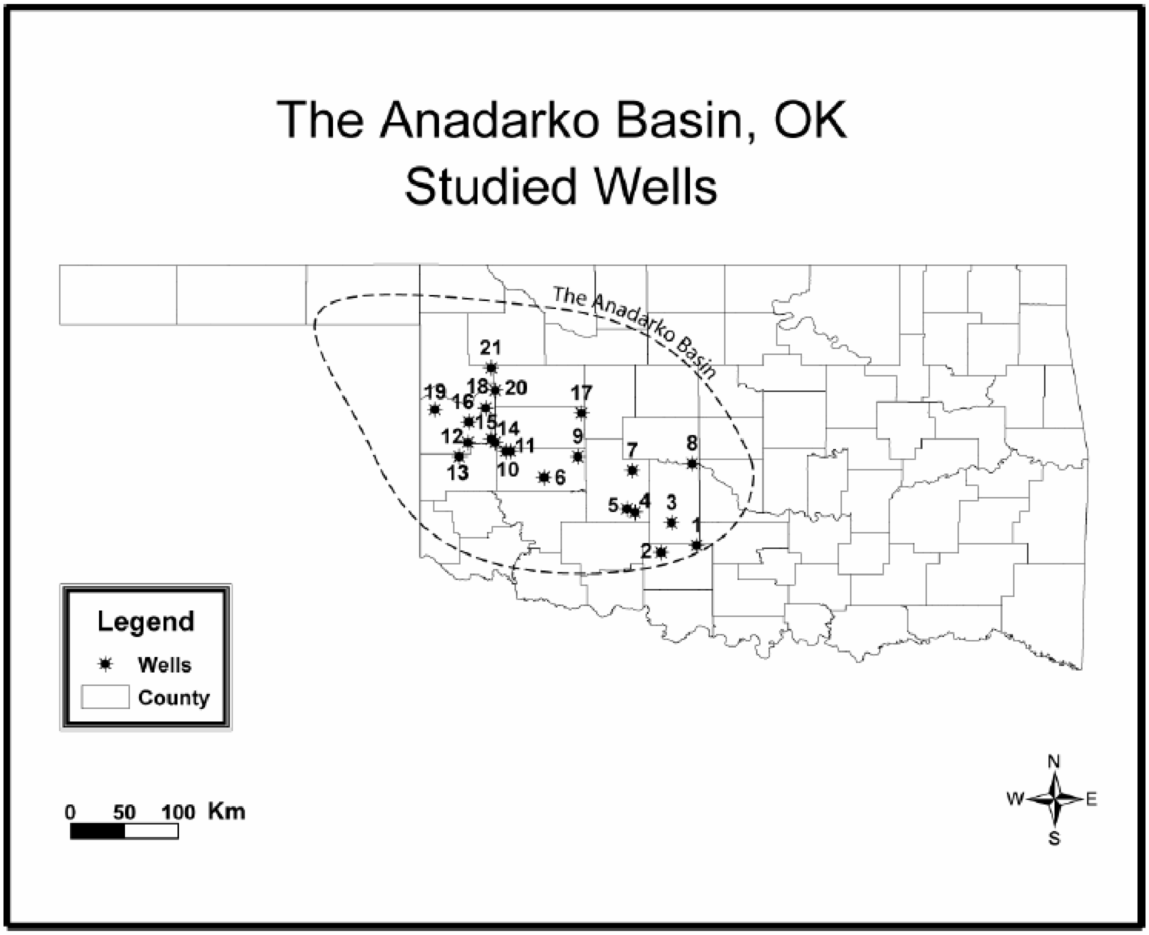

Figure 1. Location map for the Anadarko Basin showing the locations of 21 wells sampled in this study.

Another hypothesis to explain the generation and maintenance of fluid overpressures in the Anadarko Basin was gas production from a source rock (Lee and Deming, 2002). The Anadarko Basin is rich in gas: through 1985, petroleum reservoirs in the basin produced 82.2 trillion cubic feet (2.33×10^{12} m^3) of gas (Davis and Northcutt, 1989), and the ultimate recovery of natural gas from the Anadarko Basin in 1980 was estimated to be 3.1×10^{12} m^3 (Rice et al., 1989; Dyman et al., 1997).

Even though the Anadarko Basin possesses huge amount of gas and despite the fact that gas generation could be a likely source of overpressuring observed in the basin today, Lee and Deming (2002) dismissed this hypothesis because the apatite fission track data indicate unambiguously that the Anadarko Basin was uplifted and cooled starting ~40 – 50 million years ago. The amount of uplift was in the range of 1 – 3 km. As a result, the temperature in the basin dropped by 20°C and stopped the gas generation. It follows that the initial overpressure produced when the gas generation was active, should have been preserved for the last several tens of millions of years. But Lee and Deming (2002) pointed out that the containment of overpressure by layers thinner than ~100 m would require permeabilities lower than 10-25 m^2, which are 2 orders of magnitude lower than the lowest shale permeabilities ever measured or inferred (Neuzil, 1994).

If the previous discussed hypotheses, involving two widespread mechanisms, cannot fully account for production and preservation of overpressures in the Anadarko Basin over long periods of time, it is necessary to look for another model.

Capillary Sealing in the Anadarko Basin

Following the seminal papers published by Larry Cathles and his co-workers from Cornell University (Revil et al., 1998; Cathles, 2001; Shosa and Cathles, 2001), Deming et al. (2002) and Cranganu (2004) tested another hypothesis, which can be termed "capillary sealing". Capillary sealing occurs in a sedimentary basin when capillary forces act at gas-water interfaces between coarse- and fine-grained clastic rocks. Detecting capillary seals implies two main aspects: (1) detecting the presence of gas layers using geophysical logs or other data, and (2) estimating the pore throat radius of coarse- and fine-grained clastic rocks by using mercury injection (porosimetry) measurements.

Detecting Gas-bearing Layers in the Anadarko Basin

Identifying gas-bearing layers in a sedimentary basin implies a thorough and complex interpretation of information contained in well logs. We searched over 100 logs from oil and gas wells in the deep Anadarko Basin. In about half of these logs we identified multiple thin layers of gas. The procedures followed and the precautions taken to avoid any possible mistake are described in detail in Cranganu (2005).

The detection of gas-bearing layers with open-hole logs is tied primarily to the use of porosity type logs. These are the only logs generally run in open hole that are really influenced by presence of gas versus the presence of oil or water. The gas detected is in the invaded zone close to the borehole wall, or sometimes in the virgin formation if there is little to no invasion. The response of these porosity devices must be understood to fully appreciate the attitudes assumed in setting up gas detection systems. The following example (Figure 2) is representative for our technique of detecting thin gas-bearing layers in the Anadarko Basin.

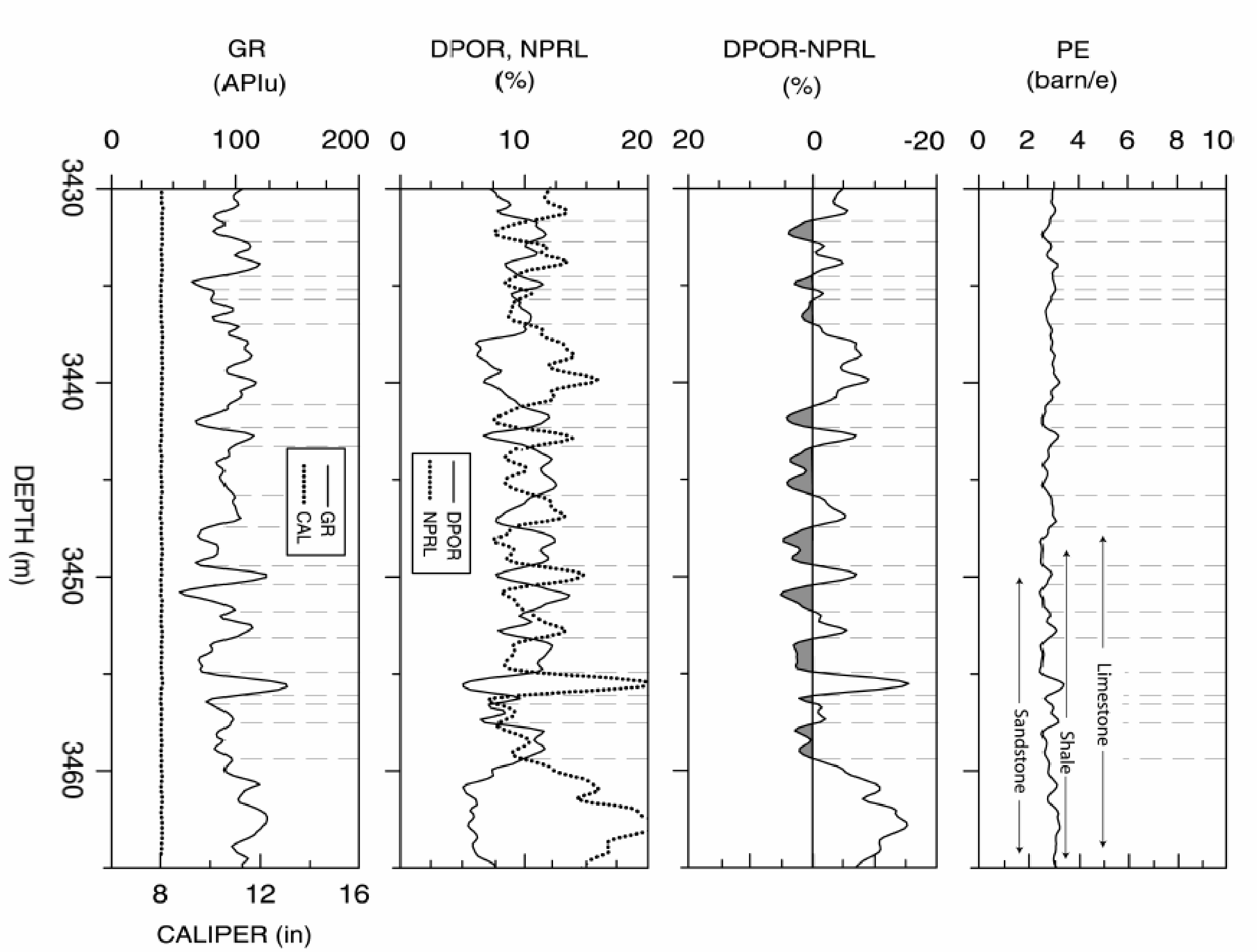

Figure 2. Well logs from 3420 m depth to 3465 m depth from well Cobb 2-27 in the Anadarko Basin (T 15 N, R 23 W, S 27, latitude 37.740°N, longitude 99.635°W). Well logs provided courtesy of Apache Oil Corporation, Tulsa, Oklahoma. Section shown is in the Prue Sand, which is a part of the Lower Desmoinesian Cherokee Group (Middle Pennsylvanian) (from Deming et al., 2002). More details and examples are found in Cranganu (2005).

Estimation of the Pore Throat Size of Clastic Rocks in the Anadarko Basin

Capillary effects can block two-phase (water and gas) flow perpendicular to alternating layers of fine- and coarse-grained clastic sediments (e.g., Berg, 1975; Surdam et al., 1997). The capillary pressure P_c in the sedimentary formations is given by the Young- Laplace equation (Revil et al., 1998):

$$P_c = (2/r)\gamma K \tag{1}$$

where γ is the interfacial tension of the gas-water interface (approximately 72 x 10^{-3} N m^{-1} at 25°C), r is the effective pore throat radius, and K is the "wetting coefficient" usually taken equal to unity. Free gas accumulates in the coarse-grained sediments. The flow of both water and gas is blocked and a gas capillary seal is formed when the saturation of gas reaches a level at which the gas phase becomes interconnected in micro "gas caps" and the pressure drop ΔP_c across the water-gas interface reaches the value (Revil et al., 1998):

$$\Delta P_c = 2\gamma(1/r_{fine} - 1/r_{coarse}) \tag{2}$$

where ΔP_c (Pa) is the pressure drop across a gas-water interface, r_{fine} (m) is the pore throat radius of the fine-grained layer, and r_{coarse} (m) is the pore throat radius of the coarsegrained layer. In the case of alternating layers of sandstones and shales, the sandstone pores are usually larger by at least a factor of 10 than the shale pores. Therefore, Equation (2) can be approximated as:

$$\Delta P_c \approx 2\gamma \;/\; r_{fine} \qquad (3)$$

To estimate the pore throat radius of shales in the Anadarko Basin, we made 21 mercury injection measurements (Figure 3) using a procedure described in Cranganu (2004). The data obtained are listed in Table 1. The average pore throat radius of the 21 samples is 2.5×10^{-8} m. The result coincides with the one obtained by Krushin (1997). With the interfacial tension γ for a gas-water interface at in situ conditions equal to 2.5×10^{-2} kg s^{-2} (Schowalter, 1979), the pressure drop ΔP_c across each gas-water interface could be as great as

$$\Delta P_c = 2 \text{x} 10^6 \text{Pa} \qquad (4)$$

If the shales are not hydrodynamically connected in three dimensions, the capillary pressure drops across each individual interfaces are additive (Shosa and Cathles, 2002). In the example from Figure 3, where we have 10 gas-saturated sands interlayered with water-saturated shales, we have 20 total interfaces producing a maximum possible pressure change of 40×10^6 Pa. In the western Roger Mills County the maximum overpressure reaches ~ 50×10^6 Pa (Al-Shaieb et al., 1994b). Thus capillary sealing due to gas-water interfaces could potentially be responsible for ~80% of the maximum overpressure observed nowadays in the Anadarko Basin.

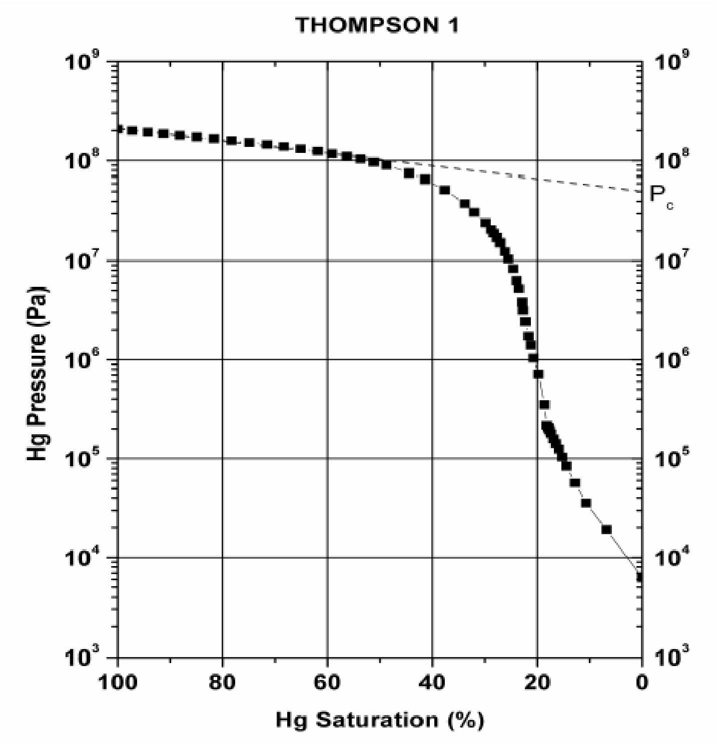

Figure 3. Mercury pressure versus relative mercury saturation for a Pennsylvanian age shale from the Thompson 1 well in the Anadarko Basin (see Table 1). The initial increase in pressure associated with saturations below ~40% is produced by surface effects. To estimate the pore throat size, we extrapolate the plateau of the curve until it reaches the zero percent saturation and then note the associated pressure; in this example, *P_c* is 50.5×10^6 Pa

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	Well name	Sample age	Location T-R-S	Lat	Long	Depth (m)	P_c (10^6 Pa)	Pore Throat Radius (10^{-8} m)
1	MYIA 1-11	Morrowan	02N-05W-11	34.660	-97.696	2019	20.92	3.5
2	THOMPSON 1	Missourian	02N-08W-36	34.601	-97.993	2643	50.50	1.5
3	W. M. WHITE 1	Missourian	04N-07W-02	34.848	-97.905	2933	62.10	1.2
4	IDA EDWARDS 2	Missourian	05N-10W-01	34.935	-98.209	1756	13.17	5.6
5	APACHE 1-26	Desmoinesian	06N-10W-26	34.964	-98.276	2344	62.00	1.2
6	KNIE A-1	Morrowan	09N-17W-26	35.225	-98.968	2338	12.66	5.8
7	WALTER STEF-FERS 1-5	Desmoinesian	09N-19W-05	35.282	-98.232	4158	70.30	1.0
8	PAYNE 17-1	Mississippian	10N-05W-16	35.341	-97.733	2713	25.18	2.9
9	AIRPORT TRUST 28-1	Missourian	11N-14W-28	35.399	-98.685	2086	48.20	1.5
10	TOELLE 1	Desmoinesian	11N-19W-07	35.443	-99.249	4121	60.00	1.2
11	MARIK 1-11	Missourian	11N-20W-11	35.443	-99.285	3260	70.30	1.0
12	BARNETT 2-3	Virgilian	11N-23W-30	35.399	-99.673	2749	49.70	1.5
13	WEATHERLY 11	Morrowan	12N-21W-03	35.545	-99.408	5777	17.20	4.3
14	BEUTLER 1-13	Desmoinesian	12N-21W-13	35.516	-99.373	4138	16.29	4.5
15	TAYLOR 1	Pennsylvanian	12N-23W-14	35.516	-99.602	3136	69.00	1.1
16	SUMMERS 1-13	Desmoinesian	14N-23W-13	35.689	-99.595	3363	17.96	4.1
17	KIPPENBERGER 1-23	Morrowan	15N-14W-23	35.761	-98.657	3261	19.72	3.7
18	SWITZER C-5-1	Desmoinesian	15N-21W-05	35.804	-99.453	3480	69.00	1.1
19	MALES 3-8	Virgilian	15N-25W-08	35.790	-99.878	2633	41.40	1.8
20	REAGAN 1	Desmoinesian	17N-20W-18	35.950	-99.372	2987	34.76	2.1
21	HALL 1-11	Morrowan	19N-21W-11	36.138	-99.408	3167	34.36	2.1

Table 1. Capillary Pressures (Pc) and Pore Throat Radius for Shale Samples from the Anadarko Basin

Conclusions

This article tries to explain the generation and maintenance of abnormal fluid pressures in the Anadarko Basin, Oklahoma, by invoking a capillary sealing mechanism, in which a pressure drop across each gas-water interface is required in order to push gas from a coarse-grained layer (usually, sandstone) into and through an overlying fine-grained layer (usually, shale). The model proposed requires the presence of thin gas layers interbedded into shale layers. Use of a suite of geophysical logs ensures the detection of these gas layers. Measurements by injecting mercury into rock pores allow estimation of the shale pore throat radius.

Acknowledgments

Acknowledgment is made to the Donors of the American Chemical Society Petroleum Research Fund (PRF Grant # 39372-AC9) for partial support of this research.

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