Evidence for a Hydrodynamic Aquifer in the Lower Miocene Sands of the Mad Dog Field, Gulf of Mexico*

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Abstract

Hydrodynamic aquifers, which are associated with tilted hydrocarbon fluid contacts, have been observed in various basins around the world. This paper presents evidence for a regionally extensive hydrodynamic aquifer in the Lower Miocene sands of the Atwater Fold Belt in the deepwater Gulf of Mexico, believed to be the first of its kind in such a deep sub-salt structure. The evidence for a hydrodynamic aquifer comprises formation MDT pressure data from various drilled structures in the Atwater Fold Belt area, as well as mapped wide-azimuth seismic data, drilled oil-water contacts and production data from the Mad Dog Field.

The inferred mechanism for creating the hydrodynamic effect is believed to be mechanical compaction and dewatering of the large column of sediments in the deepwater Gulf of Mexico. Due to increasing overburden pressure, the aquifer gradually becomes overpressured, and expulsion of aquifer brine occurs after the fracture gradient is exceeded at a weak point in the regionally connected sand system, creating an escape valve to shallower formations. It is theorized that the geographic locations of the areas of highest compaction and of the “escape valve” control the direction of flow in the aquifer.

The observed hydrodynamic aquifer has a pronounced impact on the oil-in-place distribution for the Lower Miocene sands of the Mad Dog Field, where a tilted contact caused by a hydrodynamic aquifer is required to explain the oil-water contacts observed from drilling results and seismically-mapped spill points. The presence of a hydrodynamic system in the Lower Miocene of the Gulf of Mexico may also impact the understanding of the charge history and fluid contact distribution within other reservoirs and exploration play types in this deepwater region.

Introduction

Hydrodynamic activity is created by the lateral flow of water through an aquifer, and is characterized by a pressure gradient across the aquifer. Where hydrocarbons are trapped, a hydrodynamic system often manifests itself through a tilted fluid contact (Dennis et al., 1998). This is in contrast to a hydrostatic system, where there is no component of lateral flow and the system is at static equilibrium, and hence there is no pressure gradient through the aquifer. The impact of pressure variation on tilting of hydrocarbon contacts was recognized early on by Hubbert (1967), and many examples have since been identified; for example, in the Kraka field of the North Sea (Thomasen and Jacobsen, 1994), Qatar (Wells, 1987), Papua New Guinea (Eisenberg, 1994), and Colombia (Estrada, 2000).

Bjørlykke has identified numerous mechanisms that could create hydrodynamic activity, the most prominent being influx due to meteoric (i.e. atmospheric) water. However, this mechanism cannot explain the observed hydrodynamic activity in the deepwater Gulf of Mexico. Instead, it is believed that sediment compaction due to subsidence is the most likely cause, due to the large overburden and significant rate of sedimentation.

Pressure Potential Data

The majority of the numerous exploration and development wells that have been drilled in the Atwater Fold Belt area have MDT or RFT formation pressure measurements in Miocene age sands. Some wells have formation pressure estimated from mud weight required during drilling. In general, these pressure measurements indicate that the aquifer is overpressured relative to hydrostatic, with a large number of wells in the Lower Miocene showing a similar degree of overpressure of around 3,000 psi.

Examining the formation pressures in more detail, there appears to be a noticeable trend in the degree of overpressure versus geographic location, which is observed across several fields. Creating a potentiometric plot of aquifer overpressure in the Lower Miocene versus geographic location, it is observed that the degree of overpressure decreases towards the east-northeast, at a vector of approximately 75 degrees from true North (Figure 1). There is no correlation to salinity or depth which would explain the observed variation in overpressure; instead, it is believed that hydrodynamic activity in the aquifer may be the most likely explanation.

The inferred mechanism for creating this hydrodynamic effect is believed to be mechanical compaction and dewatering of the large column of sediments in the deepwater Gulf of Mexico. Due to increasing overburden pressure, the aquifer gradually becomes overpressured, and expulsion of aquifer brine occurs after the fracture gradient is exceeded at a weak point in the regionally connected Lower Miocene sand system, creating an escape valve to shallower formations. It is theorized that the geographic locations of the areas of highest compaction and of the “escape valve” control the direction of flow in the aquifer.

The magnitude of the change in the overpressure is approximately 6 psi/mile, or 0.0011 psi/ft. An illustrative estimate of the order of magnitude of the flow rate associated with this pressure gradient can be obtained by solving for flow rate using the Darcy formula for horizontal flow (Dake, 1978):

$$q = -\frac{kA}{\mu}\frac{\partial p}{\partial x}$$

Making some broad assumptions for average permeability, reservoir thickness and areal extent, and solving for rate from the above equation converted into field units, gives a flow rate *q* of around 2,000 bbl/day. The fluid velocity associated with this flow rate is only 0.04 ft per year. Using the methodology of Bjørlykke, and assuming the flux is 10% of the sedimentation rate, then the volumetric brine flux calculated above is consistent with a basin of 90 by 90 miles subsiding at a rate of 0.1 mm/year (3.281×10^{-5} ft/year).

It can be seen from above that only a very small amount of flow is necessary to create the pressure gradient observed from well MDT data. This is consistent with the results of Yuster (1953), who found that only a remarkably small quantity of water was all that was required to create an assumed tilt. Dennis et al. (1998) showed that such small flow rates are to be expected in a layered sedimentary system where there are no pathways for vertical flow, e.g. along a fracture. In such a case, water expelled from a subsiding sedimentary basin will tend to flow laterally, assuming that an extensive and well-connected aquifer system exists.

Mad Dog Field

Discovered in 1998 in a water depth of about 4,500 feet, the Mad Dog Field lies within the Mississippi Fan Fold Belt, also known as the Atwater Fold Belt, which is a prominent contractional fold-and-thrust belt located in the deepwater Gulf of Mexico (Moore, 2001). The Mad Dog structure is a large, north-south trending, faulted, compressional anticline with the majority of discovered hydrocarbon resource in the Lower Miocene turbidite reservoirs. Interpretation from conventional core in the main reservoir interval suggests that the reservoirs are primarily amalgamated and layered sheet sands, with good porosity and permeability.

The Mad Dog Lower Miocene reservoir is subdivided into two segments – East and West – each with nearly identical oil properties. Actual oil-water contacts for both compartments were penetrated in two wells drilled to date: Mad Dog Deep-2 in the East and Mad Dog-11 in the West, shown in Figure 2. Sand extent, reservoir quality and fluid quality are laterally consistent and predictable within the Lower Miocene reservoirs unless faulted out, as observed in the crestal graben.

Following spar installation in 2004, the Mad Dog Field was brought online in January 2005. In the years since first oil was achieved, pressure support due to aquifer influx has been observed in most Lower Miocene wells with significant production history. No water injection wells have been drilled to date.

As has been pointed out by Dickey (1988), the aquifer pressure trend illustrated in Figure 1 may be caused by separate compartmentalized aquifers, and hence may not be indicative of flow. However, such an observation would be incompatible with the production history to date at Mad Dog, where significant aquifer influx is required to explain the bottomhole pressures at the production wells. There is no other reservoir drive mechanism which can explain the degree of pressure support observed. The aquifer support seen at Mad Dog is evidence of continuity of permeability in the aquifer, at least in the immediate vicinity of the Mad Dog Field.

Prior to analyzing sub-regional aquifer pressure data, the downdip extent of oil in the Mad Dog West segment was difficult to explain using the best-available structure maps based on 3-D seismic data. The oil-water contact intersected by appraisal drilling in the West segment is deeper than the mapped spill point to the southwest by around 400 feet.

In a revised interpretation, the hydrodynamic aquifer model was applied to the existing structural map, with the tilted oil-water contact defined by the regional aquifer pressure trend from offset well MDT data. The inferred tilted oil-water contact, using the pressure potential shown in Figure 1, is aligned with the apparent mapped spill point to the southwest, as shown in Figure 3.

Summary

A hydrodynamic aquifer is believed to exist in the Lower Miocene sands of the Atwater Fold Belt area, in the vicinity of the Mad Dog Field. While hydrodynamic aquifers have been noted in numerous other parts of the world, it is believed that this is the first time that evidence for a hydrodynamic aquifer has been observed in the deepwater, sub-salt reservoirs of the Gulf of Mexico.

With reference to the Mad Dog Field, a regional hydrodynamic aquifer model most easily explains the observed oil-water contacts and is consistent with the mapped structure. Regional formation pressure data suggests that the direction of flow, and hence the direction of decreasing overpressure, is towards the northeast. The effect on the distribution of oil-in-place at Mad Dog is to create a tilted oil-water contact that is most evident on the western side of the field.

The presence of a hydrodynamic aquifer system in the Lower Miocene is consistent with the production history of Mad Dog to date, and affects future development plans for the field. It may also impact the understanding of the charge history and fluid contact distribution within other reservoirs and exploration play types in this deepwater region.

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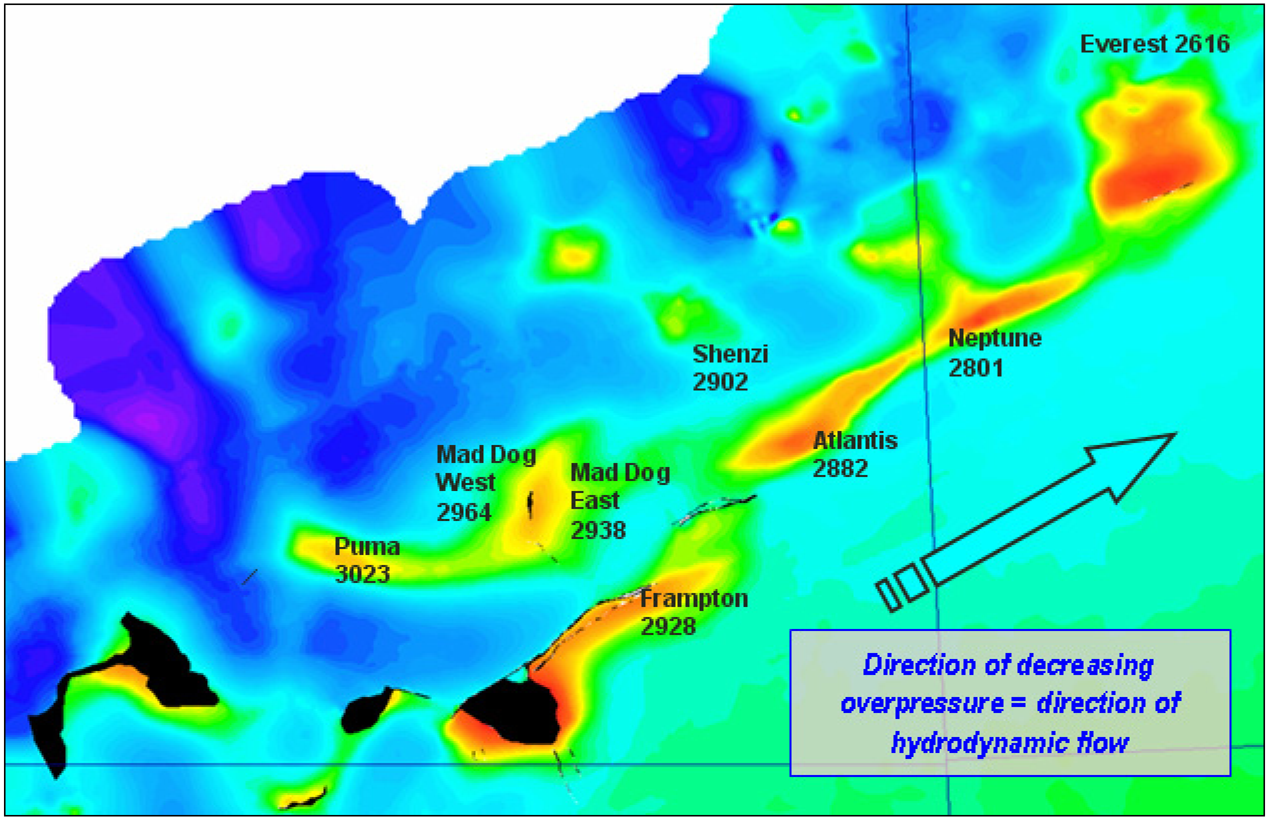

Figure 1. Potentiometric map showing degree of overpressure (relative to hydrostatic) versus location (modified after Moore et al., 2001).

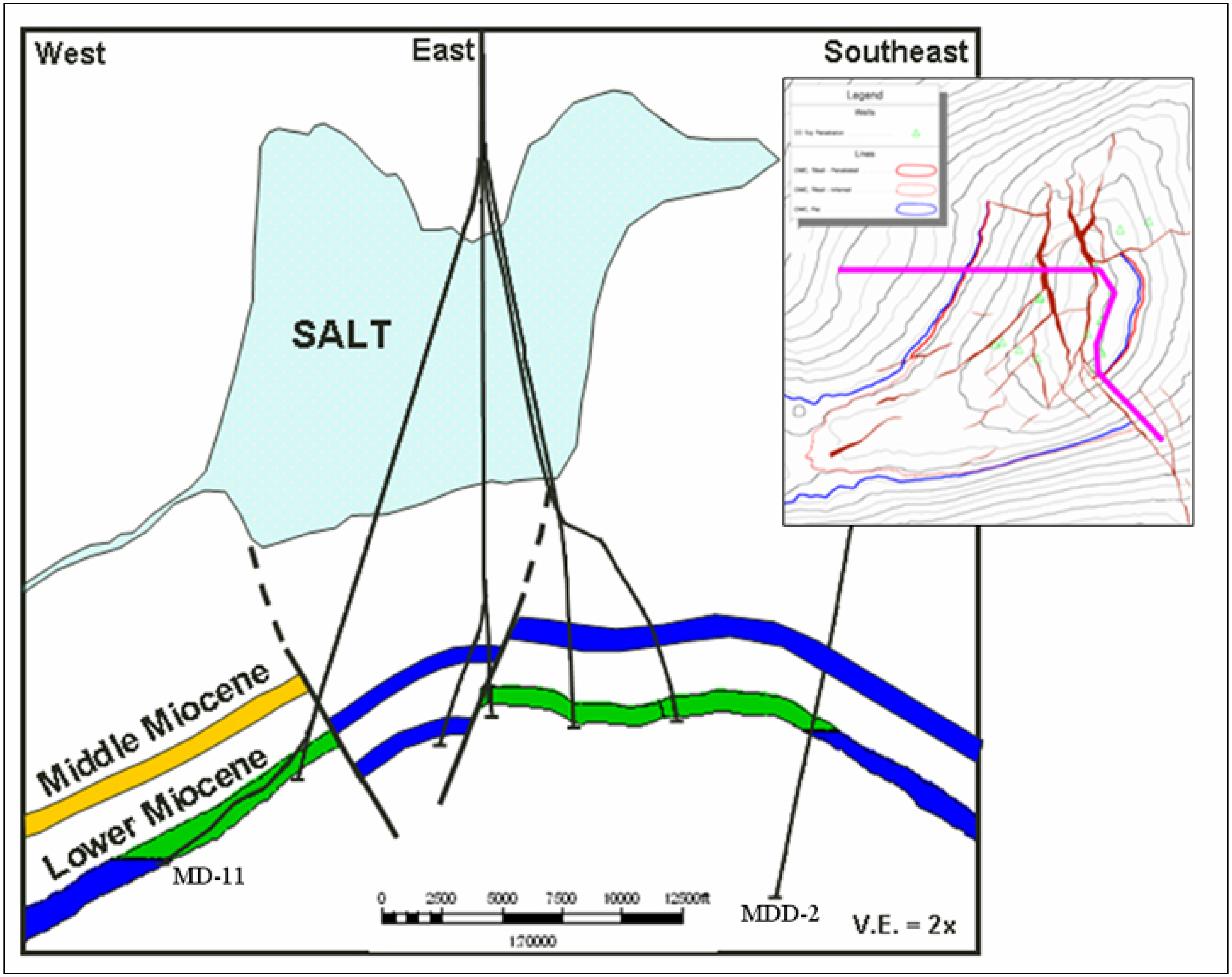

Figure 2. Schematic structural cross section of the Mad Dog Field, showing intersected oil-water contacts and trapping mechanism.

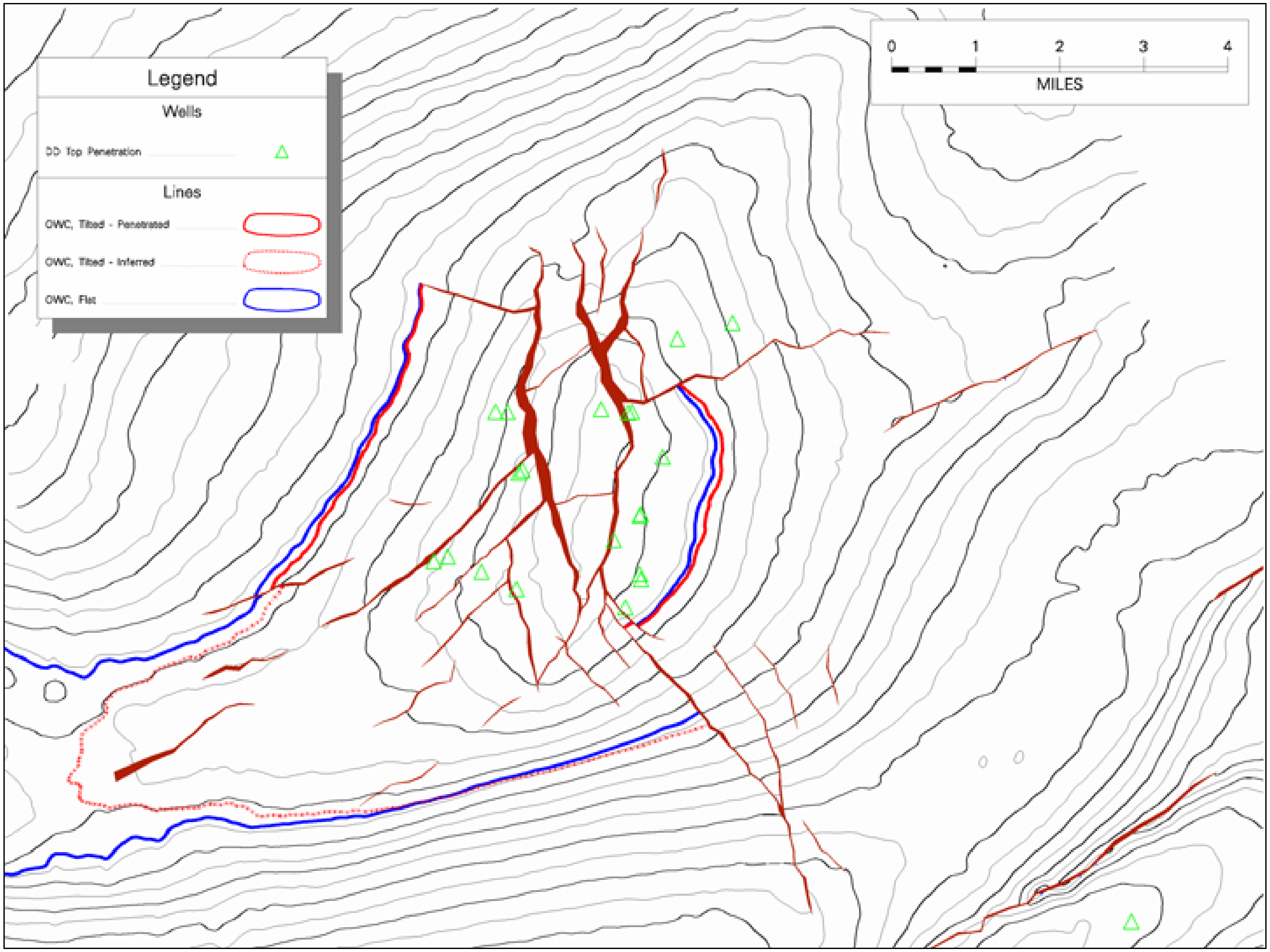

Figure 3. Structural contour map of the Mad Dog Field showing a tilted oil-water contact (red) and a flat oil-water contact (blue).