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3-D Multiphysics Modeling of a Producing Hydrocarbon Field

Abstract Thermal anomalies indicating elevated temperatures often are present in producing hydrocarbon fields. Thermal anomalies delineated by bottom hole temperatures (BHTs) are readily identified in such settings, but are difficult to interpret because the data are not equilibrium-temperature measurements, nor do they provide depth constraints on thermal anomalies (i.e., change in heat flow with depth, fluid migration, etc.). A better method to investigate the source and spatial extent of thermal anomalies (or even the background thermal regime) is with precision temperature logs, which can then be utilized to constrain subsequent modeling efforts.

This paper discusses precision temperature logs obtained over a salt dome in the Bayou Bleu hydrocarbon field in southwest Lousiana, and presents a 3-D thermal-fluid model of the dome constrained by these types of logs. The numerical model in which both an enhanced thermal conductivity contrast due to heterogeneity, and salt body characterized by a broad mushroom-like head above a thin stalk, best satisfies the observational data.

Coupling in fluid flow appears to be an important heat-transfer mechanism away from the dome only (due to the large percentage of relatively impermeable shale present around the salt). It also appears possible that the Bayou Bleu dome might have an overhanging shape which suggests the presence of unexploited targets below a possible overhang.

Keywords Multiphysics – Heat Transfer – Fluid Flow – Thermal Conductivity – Salt Dome

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1 Motivation

Elevated temperatures often are present in producing hydrocarbon fields. Their presence is attributed to the rapid upflow or migration of fluids; the effects of structure (i.e., salt domes, shale diapirs), and the effects of thermal conductivity contrasts arising from the presence of water (0.6 $Wm^{-1}K^{-1}$), gas (0.05 $Wm^{-1}K^{-1}$), and petroleum, (0.2 $Wm^{-1}K^{-1}$) with respect to that of typical basin sediments (1-6 $Wm^{-1}K^{-1}$).

Thermal anomalies delineated by bottom hole temperatures (BHTs) are readily identified in such settings, but are difficult to interpret because the data are not equilibrium-temperature measurements, nor do they provide depth constraints on thermal anomalies (i.e., change in heat flow with depth, fluid migration, etc.). A better method to investigate the source and spatial extent of thermal anomalies (or even the background thermal regime) is with precision temperature logs, which can then be utilized to constrain subsequent modeling efforts.

In previous studies, relatively simple models of the thermal refraction effect of the salt dome often do not match thermal observations: the calculated effects are generally too small. Rather than reassess the numerical model, many energy companies have instead concluded that precision temperature logs measured *in situ* in producing fields are no better than BHT data.

However, it is possible to reconcile the disparity between the observed and numerically determined thermal regime by incorporating several additional effects in the numerical model: vertical and lateral heterogeneity in the thermal conductivity structure, variable salt dome geometry, and fluid flow around the salt body. Each approach is readily implemented in COMSOL Multiphysics utilizing the both the standard Heat Transfer application mode and Earth Sciences module.

Report Documentation Page					*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE **OCT 2005**		2. REPORT TYPE			3. DATES COVERED **00-00-2005 to 00-00-2005**
4. TITLE AND SUBTITLE **3-D Multiphysics Modeling of a Producing Hydrocarbon Field**					5a. CONTRACT NUMBER
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)					5d. PROJECT NUMBER
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Research & Development Center,Geotechnical & Structures Laboratory,3909 Halls Ferry Road,Vicksburg,MS,39180**					8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S)
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**					
13. SUPPLEMENTARY NOTES **Presented at the 2005 COMSOL Multiphysics User's Conference Boston, 23-25 Oct, Boston, MA**					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

2 Temperature Logging in the Bayou Bleu Hydrocarbon Field

Recent advances in technology allow the routine acquisition of very accurate (±0.001 °C) temperature logs that record temperature vs. depth with sub-meter (0.1m) resolution. Precision temperature logs have been routinely acquired in producing, and non-producing oil/gas/geothermal wells, and successfully used to interpret small-scale lithologic variations (e.g., Blackwell and Steele, 1989; Blackwell et al., 1999; McKenna and Blackwell, 2002; McKenna et al., 2004).

Three types of temperature-logging tools are now utilized:

- Electric-line (Blackwell and Spafford, 1987; McKenna et al., 2004)
- Slick-Line (Wisian et al., 1998)
- Fibre-Optic (Distributed Temperature Systems or DTS, Forster et al., 1997)

Aside from accurate *in situ* temperatures, precision temperature logs also can help define the structure of the sub-surface salt since thermal gradients and the sub-surface temperatures in the wells are closely correlated with the location of the well relative to the apex of the dome: surface heat flow and the well-equilibrium bottom-hole temperatures increase systematically as the apex of the dome is approached.

The location of precision, detailed temperature-depth logs in 7 wells in the Mobil Bayou Bleu oil field, Iberville Parish, Louisiana in February of 1997 are shown in Figure 1. The field is located along the Gulf Coast in rocks of Oligocene to Pleistocene age above a salt dome.

The dome is located near the northern edge of the onshore salt basin in Louisiana (see Figure 2) and has been producing since the 1950's. In addition to the temperature logging, thermal conductivity was measured on 37 samples from the field including three of the wells in which the temperatures were logged. The depth of the wells logged ranged from 1825 ft on top of the dome to 9300 ft away from the dome. In spite of the difficult thermal conditions the long production history, gas pressures, and recent well disturbances, usable thermal data were obtained in every well logged.

Using the data collected in the field and in the laboratory the thermal regime of the area around the salt dome was characterized. Figure 3 shows the temperature-depth logs obtained in and around the field.

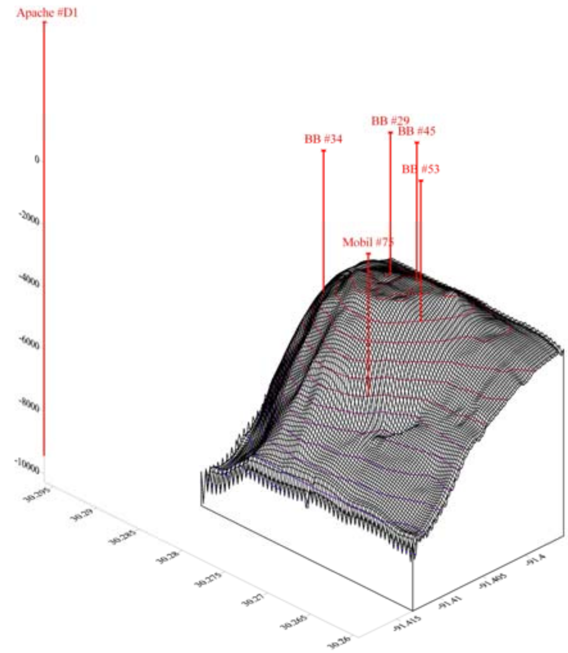

Figure 1. Well control in the Bayou Bleu Hydrocarbon Field, Iberville Parish, Louisiana. All wells with the exception of the Apache #D1 are situated over the salt dome. Below about 10000 ft, the salt structure is unknown.

Figure 2. Geologic and tectonic setting of the Bayou Bleu Hydrocarbon Field, Iberville Parish, Louisiana. From unpublished Mobil Report on Bayou Bleu Oil Field.

Also shown for comparison are the regional data from the American Association of Petroleum Geologists Geothermal Survey ofNorth America (AAPG GSNA) corrected data set. The results illustrate the increase in temperature associated with the heat flow refraction by the high thermal conductivity salt of the dome compared to the lower thermal conductivity sands and shales in the section. The wells at the top of the dome, buried at a depth of about 3000 ft, are up to 34 °F hotter than the flank well at a depth of 2000 ft. The high temperature and resulting high thermal gradient and heat flow are explained by the focusing of heat through the high thermal conductivity salt. This is analogous to the way electrical current flows more freely through a conductor than a resistor.

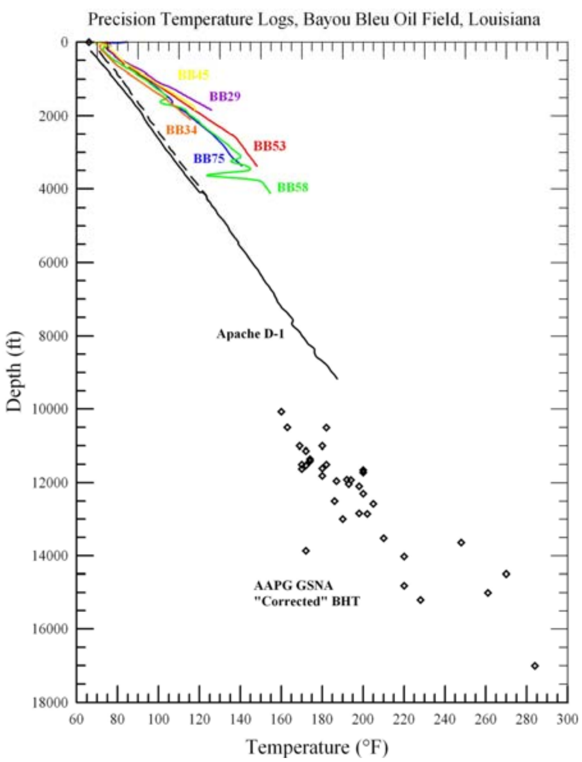

Figure 3. The offset between the temperature logs in a direct function of position around the salt dome. The Apache well is located to the northwest of the salt dome and does not encounter salt until 14000 ft, hence the temperatures in this particular well are significantly cooler at any given depth.

3 Multiphysics Modeling

The average thermal gradients (i.e., *in situ* temperatures), thermal conductivity, and consequently heat flow in the upper 2000 ft of the wells, all reflect to some extent the position of the well with resepct to the salt dome. The thermal effect of salt has been modeled extensively (e.g., Selig and Wallich, 1966, O'Brien and Lerche, 1984, etc.). However, there has been little comparison of observed temperatures (including BHT data) to model results and no detailed thermal data of the nature collected in this field. The high thermal conductivity of salt and anhydrite, about 6.0 $Wm^{-1}K^{-1}$ compared to sediment values of 1.0 to 2.5 $Wm^{-1}K^{-1}$, causes heat to flow preferentially through the higher thermal conductivity salt and to be focused in the area above the dome. As a result of the heat focusing, heat flow anomalies (i.e., high temperature anomalies) should be found over salt domes. In fact, high heat flow is one way to differentiate salt from shale diapirs (unless they are actively forming). Thus the observations in the Bayou Bleu field are expected from idealized considerations.

Three simple models were calculated for a preliminary comparison of the observed results to models. The upper 10000 ft of the model salt dome shape is taken from the contour map and sections of the salt dome (unpublished Mobil Report). A SE-NW section of the dome is shown in Figure 4. The shape of the dome is well known within the depth limits of the drilling. Below 10000 ft the shape is based only on limited, vintage seismic information. Thus a suite of extreme models of the shape were investigated.

The parameters of the three models are summarized in Table 1. In all of the models the dome had a shape to a depth of 10000 ft based on the contours from drilling (Mobil Report) and had an almost square cross section and vertical sides from that depth to 40000 ft (see Figures 5 and 6). The solution used the COMSOL Heat Transfer Application mode stationary algorithm. Transient effects are probably not important as the dome must have been essentially in place by the end of Miocene time. The boundary conditions were no heat flow through the sides and constant heat flow (50 mWm^{-2}) through the bottom of the model at 45000 ft. This high basal heat flow value was needed to come close to the observed heat flow values overall. The thermal conductivity was assumed to be constant with temperature. In the second and third models the shape of the dome was assumed to be a mushroom with the stalk, below 10000 ft, or about 1/2 the diameter of the head of the dome. In the first and second models the thermal conductivity values assumed were 2.0 and 6.0 $Wm^{-1}K^{-1}$ for the sediment and salt respectively. In the third case the contrast was increased by lowering the sediment conductivity to 1.5 and raising the salt thermal conductivity to 6.5 $Wm^{-1}K^{-1}$. The thermal conductivity of the salt was taken to be that of the Avery Island salt dome from the report of Durham and Abey (1981). The steady-state themral structure is shown in Figure 7. The three models are compared by looking at the 2000 ft temperatures observed in the wells and predicted by the models at 2000 ft (Figure 8).

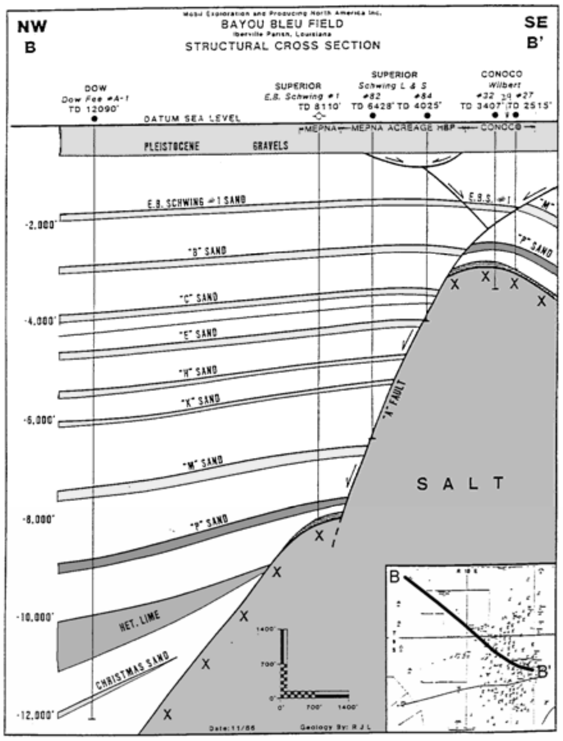

Figure 4. A SE-NW section of the Bayou Bleu salt dome. . From unpublished Mobil Report on Bayou Bleu Oil Field.

Table 1. Numerical Models.

Model A: *Two component model comprising shale (k = 2.06 $Wm^{-1}K^{-1}$ and salt (k = 5.5 $Wm^{-1}K^{-1}$). Surface of salt is as defined by contour map, with edges extrapolated to a depth of 10000 ft. Below 10000 ft, sides of the salt dome are subvertical to a depth of 40000 ft. Solid salt layer from 40000-45000 ft.*

Model B: *Same two components as for Model A, but salt dome is cut off at a depth of 10000 ft. The head of the dome is attached to the basal layer by a vertical cylindrical stalk of 2000 ft diameter, centered at 30.273°N, 91.401°W.*

Model C: *Same as Model B, but with shale (k = 1.5 $Wm^{-1}K^{-1}$) and salt (k = 6.5 $Wm^{-1}K^{-1}$).*

The size of the contrast in heat flow and in the temperature at 2000 ft (for example) is difficult to match with reasonable parameters. The only model of the three that approximates the observed temperature differences is the third model with a mushroom shape and an extreme thermal conductivity contrast. The model matches the field data very closely, but still predicts a lower than observed temperature at the Apache #D1 well.

Visgarda et al. (1985) investigated the thermal effect of a dome further south in Louisiana of similar dimensions and with thermal properties similar to those used in our model. The dome was the West Bay dome on the delta of the Mississippi. The top of that dome is deeper at about 8000 ft, compared to the

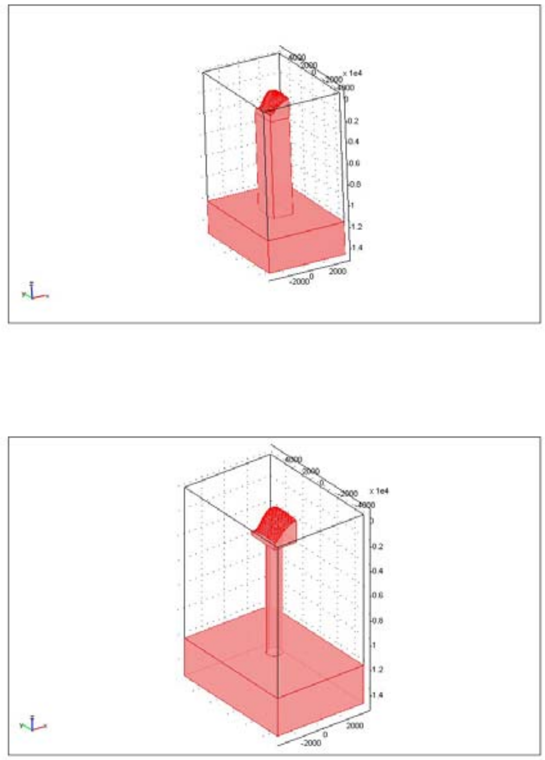

Figure 5. Numerical model A (top) and C (bottom). The above finite-element models are 5,000 x 5,000 x 15,000 m, and contain approximately 145,000 elements.

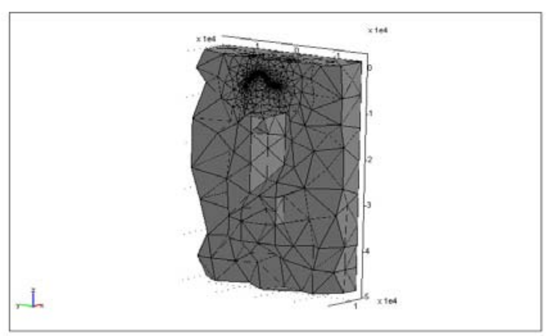

Figure 6. Example finite element mesh from numerical model A, containing about 145,000 elements.

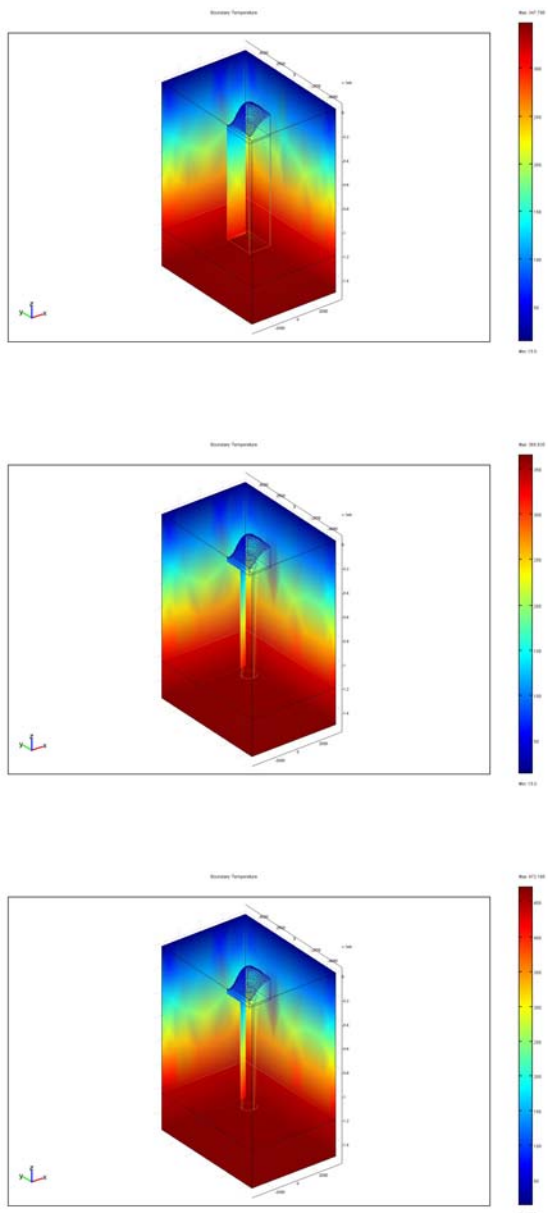

Figure 7. Steady-state thermal structure, numerical models A (top) and B (middle) C (bottom).

Bayou Bleu dome, and the diameter is 15000 ft compared to about 5000 ft. They used sediment thermal conductivities similar to those found in the measurements in this report. In particular they used a thermal conductivity of 2.0 $Wm^{-1}K^{-1}$ for the upper section (to a depth of about 10000 ft) and thermal conductivities varying from 1.5 to 1.7 $Wm^{-1}K^{-1}$ for the deeper section. They compared their results to a few BHT points and considered that they could explain the observed increase in temperature near the dome by the refraction effect. One of their models had a conductivity of 1.5 $Wm^{-1}K^{-1}$ for much of the sediment section indicating that they also saw the need for a high conductivity contrast.

According the analytical models of O'Brien and Lerche (1984) the temperatures should be higher in the area around the dome than the background down to a depth of about 1/2 of the vertical extent of the dome. The temperatures in the Apache #D1 well do not appear to approach the background in the depth of 9000 ft suggesting that the dome goes deeper than 18000 ft which is consistent with regional tectonic observations. The data are not very precise, but suggest that the salt domes are rooted at a depth of about 40000 ft.

A number of different factors could explain the difficulties in matching the observations could be a number of different factors. There may be lateral thermal conductivity contrasts not taken into account in the models. For example the Apache #D1 well may have a higher average thermal conductivity than the wells over the dome due to different sand/shale ratios and a greater presence of hydrocarbon on the pore space of the section over the dome. Other factors may include the prescense of fluid flow off the dome summit. To investigate these possibilities, we incorporated a heterogeneous thermal conductivty structure to approximate the layering of shale and hydrocarbon saturated layers prsent around the salt dome (see Figure 4).

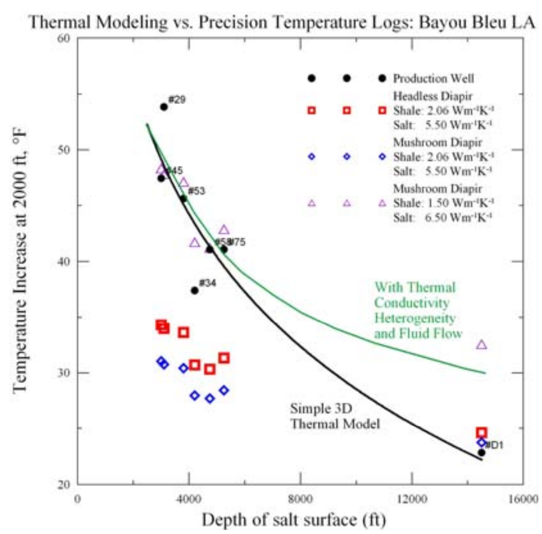

Figure 8. Observed and Predicted temperature anomaly at 2000 ft due to salt body and thermal conductivity heterogeneity and pervasive fluid flow around the salt dome.

The implemtation is straightforward in COMSOL via a 2D interpolation function, and results in the thermal conductivity structure is shown in Figure 9. The effect of adding the hetogeneity and 2 way coupling heat transfer and fluid flow around the salt dome (governed by Darcy's Law via COMSOL's Earth Sciences Module) is shown on the heat flow at 2000 ft in Figure 10.

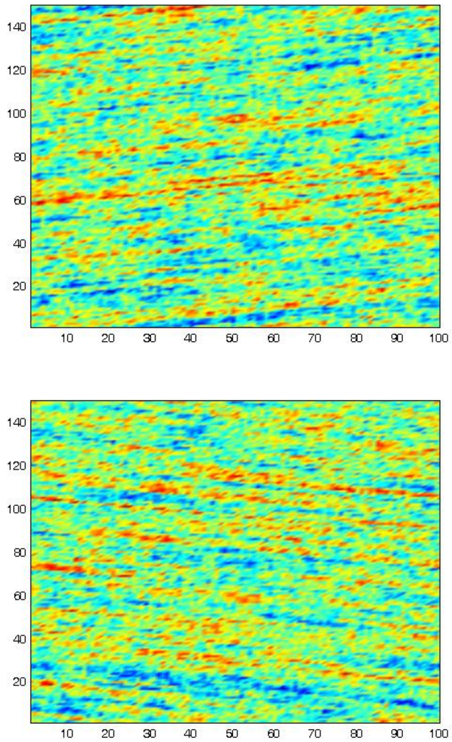

Figure 9. 2D layered thermal conductivity structure around the dome: left side of salt dome (top), and right side of dome (bottom).

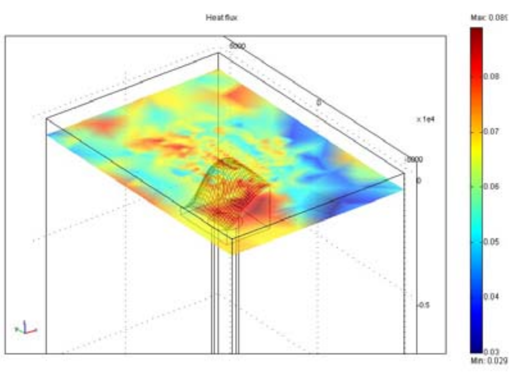

Figure 10. Effect of 2D layered thermal conductivity structure around the dome on heat flow at 2000 ft.

Overall, it is clear from Figure 8 that the misfit between the numerical models and observed temperature logs is reduced by approaching the problem via multiphysics. While other models need to be investigated, it appears possible that the multiphysics approach has validated the overhanging shape of the Bayou Bleu dome suggesting the presence of unexploited targets below the overhang.

Acknowledgements Data collection was performed with Ken Wisian and was supported by Mobil Research Lab. Discussions with Graeme Beardsmore helped formalize the modeling approach. Permission to publish was granted by Director, Geotechnical & Structures Laboratory.

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