Analysis of Convective Heat Transfer in Deformed and Stratified Aquifers Associated with Frasch Thermal Mining

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Abstract

This paper presents numerical experiments designed to simulate heat transfer in deformed, stratified geologic formations during Frasch thermal mining operations in the Delaware Basin. In such operations, superheated water (163°C) is injected into permeable ore zones to melt and mobilize sulfur. The efficiency of Frasch mining depends largely on various aspects of hydrologic controls and geologic factors, such as directing heat flow toward target areas and minimizing heat dissipation through advection and conduction in ore zones. Numerical modeling techniques were used in the search of an optimum thermal mining strategy for maximum sulfur recovery in various geologic settings present at the Culberson Mine, west Texas. The sample calculations illustrate heat transfer patterns in inclined, folded, and fractured geologic formations. Important results presented include the controls of geologic structures on directions and rates of heat transfer and ground water flow, a display of field evidence for the occurrence of thermal convection in permeable ore zones, and a depiction of heat transfer during a thermal mining operation proceeding down-dip along an inclined geologic unit. Modeling results and field data strongly support the hypothesis that thermal convection occurs and controls the heat transfer process in inclined ore zones. *Simulations further suggest that the current* thermal mining practice, which proceeds down-slope along an inclined ore zone, may result in lowered ultimate sulfur recovery. In this mining approach most heat migrates up-slope where the rock's permeability is enhanced by previous sulfur extraction, rather than down-dip toward the target area.

Introduction

The Culberson sulfur mine, located in the west-central section of the Delaware Basin, west Texas, uses the Frasch-mining process to extract elemental sulfur from the Upper Permian Salado Formation. This thermal mining operation involves the injection of superheated water (163°C) into the ore zone to melt and extract sulfur. Bleed-water wells are used for the control of ground water flow and heat transfer. The movement of hot water toward the target area is enhanced by withdrawing cooler ground water, in the ore zone, through cold-bleed water wells installed in front of current production areas. Hot-bleed water wells are used to recycle spent, heated formation water in depleted areas. The production efficiency of thermal mining depends on how much heat is directed toward the target area and how well the host rocks and the overlying confining units are capable of retaining heat.

Subsurface injection of hot water influences ground water flow and heat transport. The interaction between ground water and heat flow is coupled through changes in fluid density, viscosity, and advection velocity. Molz et al. (1983) and Buscheck et al. (1983) were among the first to use a computer model to examine heat transport associated with thermal injection in confined, horizontal aquifers. Heat transfer within inclined and folded rocks present at the Culberson Mine may exhibit more complex patterns. Domenico and Schwartz (1997) indicated that there is always a convective motion in a sloping or folded geologic unit where the isotherms are not parallel to layer boundaries. Free and forced convection have been postulated to occur in geologic settings where lateral temperature gradients exist and density and velocity fields become interdependent (Davis et al. 1985; Ludvigsen et al. 1992; Lee 1997). The existence of thermal convection in geologic formations is usually inferred from observed temperature or salinity trends (Blanchard and Sharp 1985; Hanor 1987; McKenna and Sharp 1998). A thermal convection event may also be recorded by reaction-induced mineralization and diagenetic patterns in rocks (Hanor 1987; Wilson et al. 1990; Raffensperger 1997; Lee 1997). Field data such as temperature logs and sulfur production rates provide direct evidence for the complex heat transfer system during thermal mining. This paper describes field-scale modeling experiments designed to explore the heat transfer pattern in inclined, folded, and faulted geologic formations. The predicted results can be compared to temperature distribution data observed in the field, providing constraints on possible heat transfer processes associated with the Frasch-mining operation. These models may also be used in the search for an optimum mining strategy for thermal mining within various geologic settings.

Geology and Ore Genesis

The Culberson sulfur deposit (Figure 1), part of the Rustler Springs district, is one of the largest commercial sulfur deposits in the world. This bioepigenetic sulfur deposit occurs as a replacement of calcium sulfate minerals in the Upper Permian Castile, Salado, and Rustler Formations (Crawford and Wallace 1993). These lithostratigraphic units represent a series of thick evaporites that deposited in the Delaware Basin during the Late Permian when the influx of sea water became restricted. During post-Permian time the basin was deformed by the Laramide orogeny and by Basin and Range uplift and faulting. The uplift and eastward tilting of the basin enabled hydrocarbons to migrate up dip by buoyancy toward the basin's western margin, while meteoric water recharged basinward along the elevated areas. Unique biochemical processes associated with this hydrologic regime were responsible for the formation of elemental sulfur. Sulfate-reducing bacteria used migrating hydrocarbons and sulfate within the evaporites to produce hydrogen sulfide (H_2S). The H_2S was then oxidized by infiltrating meteoric water to form elemental sulfur (Hill 1996).

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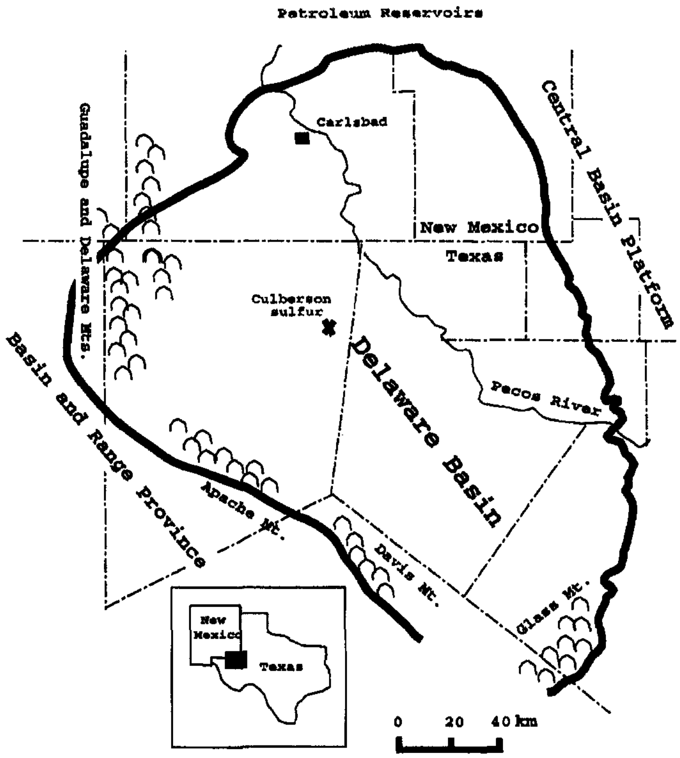

Figure 1. Simplified location map of the Culberson sulfur mine in west Texas.

The Castile Formation is the oldest sulfur mineralized unit, consisting mainly of anhydrite and calcite. The overlying Salado Formation, up to 700 m thick, is the main sulfur host rock in the basin; at the Culberson Mine, the Salado has a maximum thickness of 180 m. The mineralized zone is characterized by replacement calcium carbonate with vug-filling native sulfur, dolostone, and clastic breccias. Gypsum, mudstone, and anhydrite dominate the non-mineralized zone. The mineralization process focused on permeable brecciated zones generated by solution collapse of halite and sulfate beds. The contact between the mineralized Salado Formation and basal Rustler Formation is marked by a thin bed of clay. This clay unit includes calcareous claystone, siliceous mudstone, with fragments of gypsum, replacement limestone, and post-Salado quartz pebbles. Although absent in some areas, the clay layer acts as a confining unit to ground water and mineralizing fluids. The Salado Formation is overlain by the predominantly non-mineralized Rustler Formation, which consists mainly of anhydrite, gypsum, and silty dolomite.

Frasch Mining Operation

The Culberson ore body is a stratabound replacement type deposit characterized by complex paleokarst features including breccias and mildly deformed strata. Conventional Frasch mining techniques were developed on diapric "dome" sulfur deposits, which are efficiently confined and structurally simple. The process of Frasch mining involves the injection of superheated water into the ore formation followed by the extraction of molten sulfur. Due to the complex geologic structures at the Culberson Mine, a non-conventional approach to Frasch mining is used to mobilize and extract sulfur (Figure 2). At Culberson, operational tactics involve a series of bleed wells, including hot-bleed and cold-bleed wells to control the flow of heat and ground water. The hot-bleed wells are located behind the advancing production front. These wells are used to recycle hot formation water from exhausted mining areas, through the water heating/processing plant, and back to production

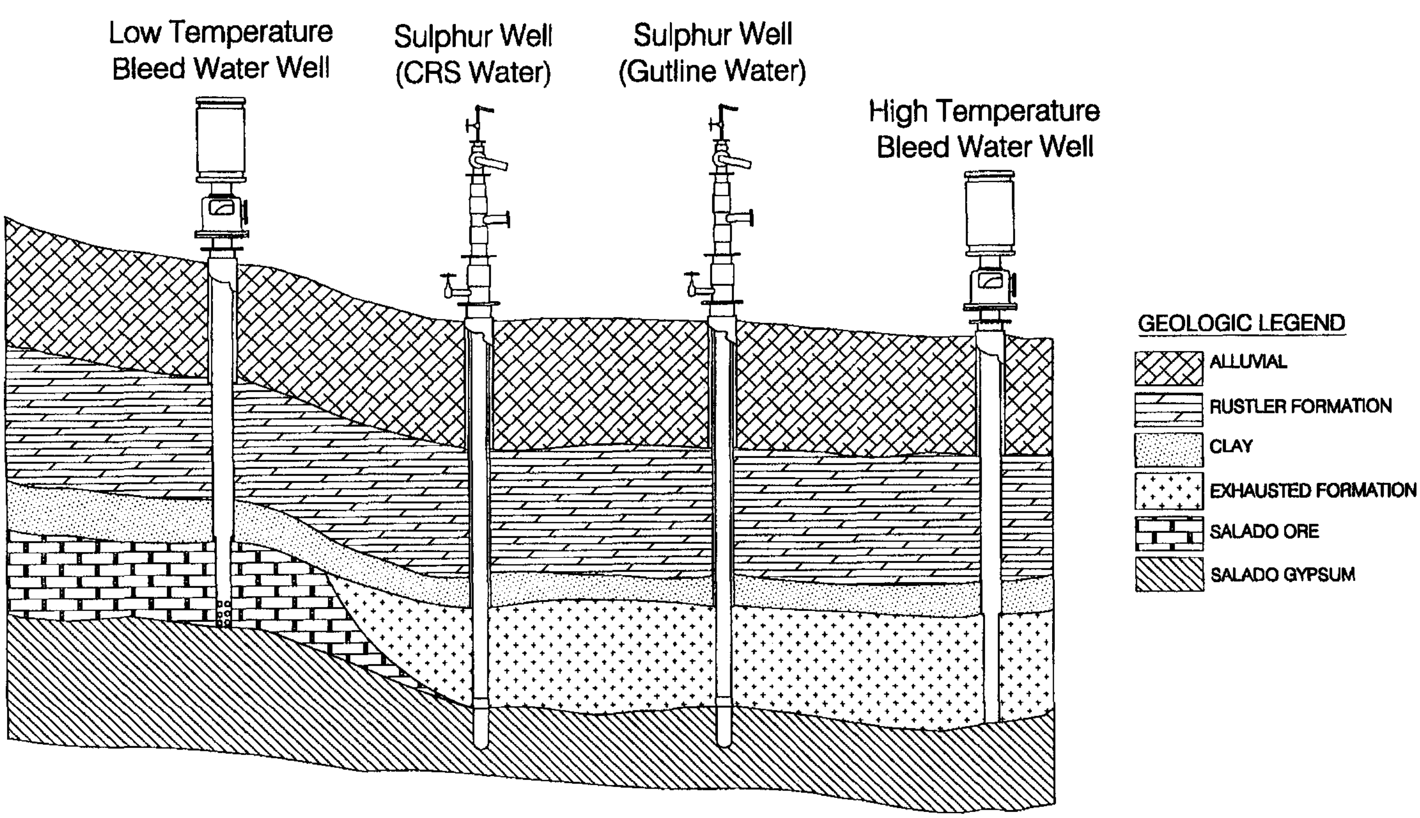

Figure 2. General depiction of the Frasch mining operation. Hot-bleed water wells draw out hot, spent formation water and recycle it through the processing plant for use in the production area. Cold-bleed water wells withdraw cooler water from the bottom of the formation to direct heat transport from injection wells to target production areas. Injection/production wells are located between the hot- and cold-bleed wells.

wells located at the target area. The recirculation of this water helps to conserve energy as well as eliminate waste water. Cold-bleed water wells are located in advance of the production front to withdraw cold water from the bottom of the formation. The effect of cold-bleed wells are threefold: (1) they govern the direction of heat transfer within the formation; (2) they heat up the projected target area for future mining; and (3) they remove high density water. Production wells are a combination of both pumping and injection (Figure 2). These vertically drilled wells are located between the cold- and hot-bleed wells and define the production front. Casing is set at the top of the sulfur-bearing formation and piping is continued through the mineralized limestone and anchored into the underlying, unaltered anhydrite. High-pressured mine water (150 psi or 1 MPa at 155 to 163°C) is delivered to the well, where it enters the formation through perforations in the well casing. This flow of heated water creates an inverted cone of elevated temperatures, with the maximum temperatures located at the bottom of the production well. When the temperature reaches 115°C, the melting point of sulfur, sulfur is mobilized and flows by density difference to the bottom of the production line. Molten sulfur initially rises into the well due to both the pressure head of water and liquid sulfur. The liquid is then lifted to the surface by compressed air. Once at the surface, the liquid sulfur is temporarily stored in relay pans where production rates are measured. The Frasch mining operations maintain sufficient pressure and fluid velocity of the superheated injected water to prevent downhole vapor-phase formation. Formation of a vapor phase in the vicinity of a well can cause differential-pressure collapse of downhole production tubulars and failure of heat exchangers and centrifugal booster pumps.

Heat Transfer Model

The major factor affecting thermal mining efficiency is the heat flow between injection and bleed-water wells. The transfer of heat in media can occur by conduction, advection of ground water, and radiation. Conductive heat transfer arises from the temperature gradient. The conduction process, controlled mainly by thermal conductivity of porous media, occurs even in static ground water. Advective or convective heat transfer is the movement of heat by migrating ground water. Radiactive heat transfer can be neglected in shallow hydrologic conditions because sediments and rocks are opaque to infrared radiation emitted by a body.

The energy (enthalpy) conservation equation describing heat transfer by conduction and advection may be expressed as

$$\rho_{sm} C_{psm} \frac{\partial T}{\partial t} = \nabla \cdot K_t \nabla T - \rho C_p \nabla \cdot (q\, T) \qquad (1)$$

where T is temperature (°C), ρ_{sm} is the density of saturated media (g/cm^3), K_t is thermal conductivity (cal/cm sec °C), q is fluid specific discharge (cm/sec), and C_{psm} and C_p are the specific heat capacity of the saturated media and fluid (cal/g °C), respectively. The first term on the right side of the equation gives the heat transfer by conduction through sediments and pore fluid. The second term calculates heat transfer by ground water advection. The left side of the equation expresses that total enthalpy change is transferred to both the fluid and solids under thermal equilibrium condition.

Models couple the simultaneous flow of heat and ground water to calculate thermal regimes, as well as calculating the effect of buoyant forces in driving fluid convection. Buoyant forces arise whenever fluid density, and hence temperature, vary laterally.

Table 1
Porosity, Permeability, and Thermal Conductivity Used in the Hydrologic Models

	Porosity (%)	Permeability (darcy or μm^2)	Thermal Conductivity[1] (cal/cm sec °C)
Confining unit	50	10^{-4}	3.15×10^{-3}
Ore zone aquifer	30	10^{-2}	4×10^{-3}

[1]$K_t = (5.35 - 4.4\,\phi) \times 10^{-3}$; ϕ is porosity of rocks.

When density and temperature vary laterally fluid convection occurs spontaneously as free convection. In such cases flow velocities and temperature fields become interdependent. Fluid motion driven by external forces is considered as a forced convection. In the model there is a combination of both forced and free convection; forced due to thermal injection and free due to density and temperature gradients.

Numerical Simulations of Heat Transfer

A numerical model, Basin2 (Bethke et al. 1993), was used to simulate ground water flow and heat transfer within inclined, folded, and faulted media. The model solves two-dimensional coupled transport equations for ground water flow and heat transfer using the finite-difference method. The model can describe flow and heat transport patterns within many types of geologic structures. Several sample calculations are presented to demonstrate the heat transfer patterns in the inclined, folded, and faulted geologic structures present at the Culberson Mine. The cross section used in these simulations is 1.6 km wide and composed of a basal ore-bearing formation overlain by a wedge of confining sediment. Porosity, permeability, and thermal conductivity used in these calculations are shown in Table 1 unless otherwise indicated. We specify a constant fluid salinity of 0.5 molal in the calculations. The choice of this value represents the average chemical (salinity) analysis of ground water collected in ore zones. Molten sulfur has little influence on the salinity of ground water because it has a higher density (about 2 gm/cm^3) than water and migrates as a separate phase. Basin2 calculates ground water density as a function of temperature, salinity, and pressure, from a correlation developed by Philips et al. (1981) for NaCl solution. The model calculates viscosity from the fluid temperature and salinity by interpolating from a tabulated table compiled by Phillips et al. (1981). The correlation is known to be valid for $10 < T < 350$°C, m (salinity) < 5 molal, and P < 50 MPa. In Frasch mining operations, the ore-bearing aquifer is heated from below by the hot water injected from the upper perforations located near the bottom of the production wells (Figure 2). In the model, basal heat flow is set to be 55 heat flow units (1 HFU = 10^{-6} cal/cm^2 sec) at assumed injection points so that maximum ground water temperatures are close to the temperature of injected water, about 163°C.

We set steady-state simulations, and in doing so implicitly assume that with time the fluid convection does not oscillate. The consistent "S" patterns of field temperature profiles, as described later, suggest that fluid convection does not oscillate during the thermal injection operation. It should be noted that three-dimensional transient modeling is required if the calculation is aimed at reproducing (matching) temperature distribution in the field. The main purpose of our modeling, however, is to examine and compare heat transfer patterns and heat dissipation processes in various geologic structures.

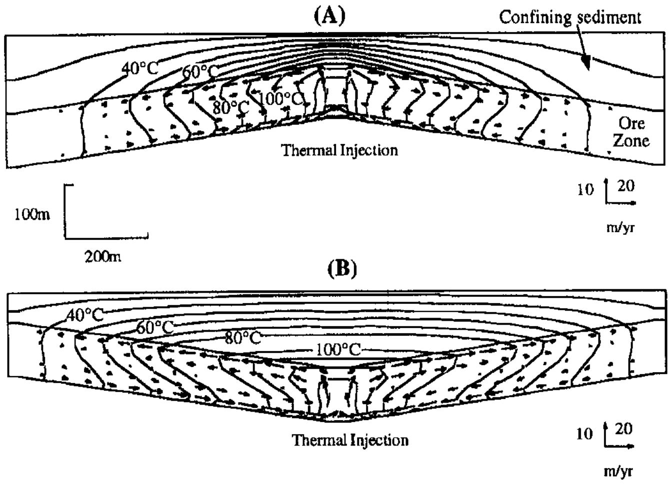

Figure 3. (a) Model of thermal injection along an anticlinal structure. Contours represent temperature isotherms (in °C). Arrows show velocities and direction of thermal convection driven by buoyancy forces. (b) Thermal injection along a synclinal structure. Heat is efficiently retained by the thick confining unit. A larger cone of depletion develops in this case than in the anticlinal structure (a).

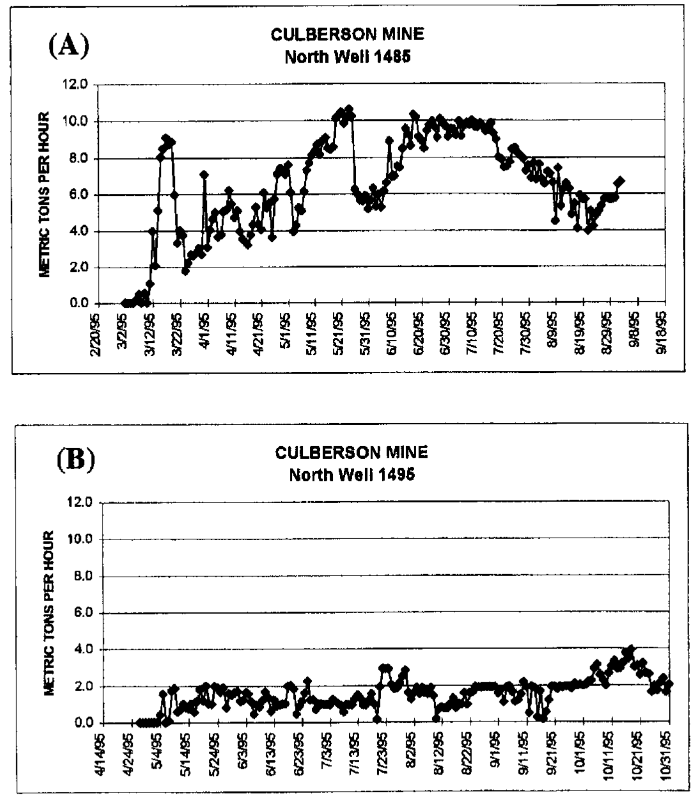

Figure 4. Production rate comparison (in metric tons per hour) for wells tapping synclinal (a) and anticlinal (b) structures.

Although three-dimensional transient modeling could better represent thermal mining systems and provide simulation-optimization techniques for a proper choice of well configuration (number and location), the modeling efforts may be limited by the availability of geologic and hydrologic data. Simulations in three-dimensions may not warrant new understanding if the major conclusions could be obtained from simpler two-dimensional simulations.

The first model simulates heat transfer that would result from thermal injection along the axis of an anticline structure. The model predicts that a plume of ascending hot ground water develops along the anticline axis, above the point of thermal injection (Figure 3a). The plume moves at a rate of several meters per year along the top boundary, cools, sinks, and then migrates along the lower boundary toward the axis. Thermal injection along the axis of a syncline structure produces a similar convective pattern (Figure 3b). In the syncline case, however, a broader cone of depletion is generated because heat is more efficiently retained by the thick con-

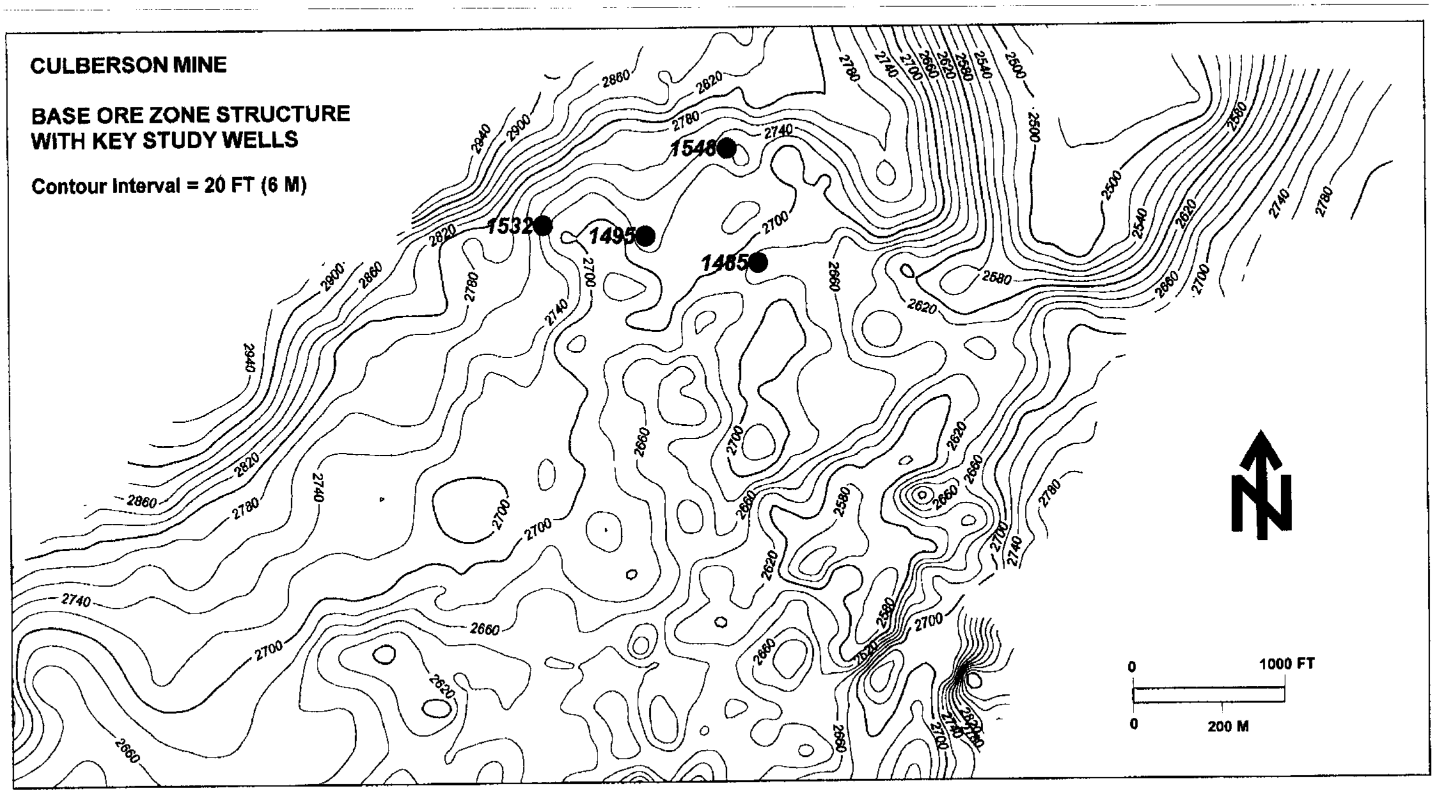

Figure 5. Structure map (contours in feet above sea level) of the basal ore zone at the Culberson Mine.

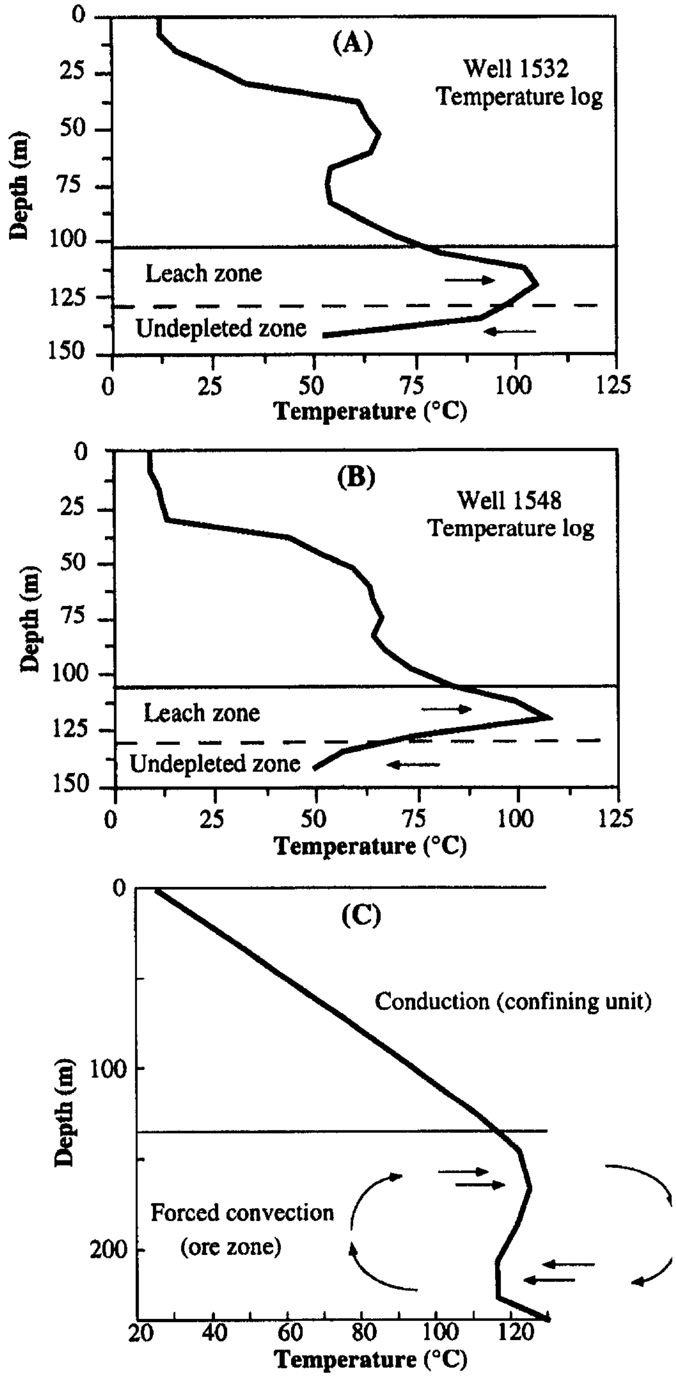

Figure 6. Measured temperatures vs. depth profiles of well 1532 (a) and well 1548 (b). Wells locations are shown in Figure 5. (c) Calculated temperature profiles about 20 m from a thermal injection point (Figure 3b). The results demonstrate the alteration of the conductive field by convection in the permeable ore zone. This reverse "S" pattern shown in both field and calculated data indicates the occurrence of thermal convection. Nonlinear temperature profiles also occur in a permeable limestone unit embedded within the thick confining Rustler Formation (a and b), supporting that there is always a convective movement in dipping aquifers provided that isotherms are not parallel to layer boundaries.

fining sediment overlying the syncline structure. The modeling results in Figure 3 explain why higher sulfur production rates were obtained in wells drilled near the syncline axis than those near the anticline or "dome" structure. For example, higher production rates, up to 10 metric tons per hour (TPH), were observed in well 1485 tapping a structurally low (small syncline) ore zone while lower recovery rates, less than 4 TPH, were produced from well 1495 min-

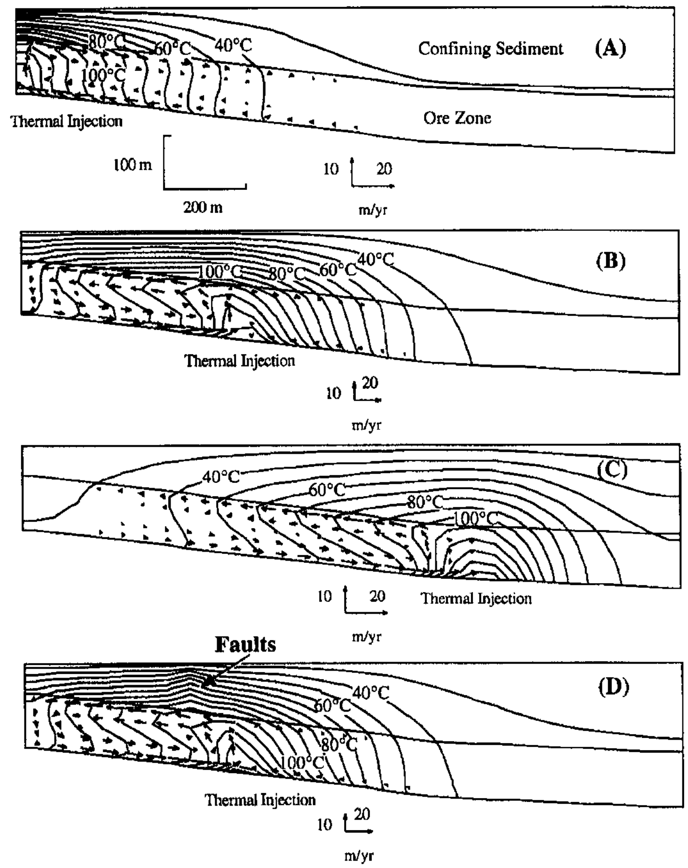

Figure 7. Simulations of thermal injection proceeding along an inclined layer. (a) Initial thermal injection on the top of the dipping slope. (b) Simulation of injection in the middle of the dipping interface. (c) Final stage of injection near the bottom of the dipping slope. Rather than moving down-dip to the target area, most hot fluids migrate up-slope where sediments have become more porous and permeable due to previous sulfur mining. The modeling results suggest that production rates will decrease as thermal injection gradually proceeds down-slope. (d) Fault model showing heat loss through fractures in overlying confining unit. The hydraulic conductivity of the fault is set to be 10 darcy.

ing a structurally high ore zone (Figure 4). The basal ore zone structure surrounding those wells is shown in Figure 5.

Field temperature data acquired through temperature logs of wells supports the thermal convection patterns predicted in Figure 3. Both observed (Figures 6a and 6b) and calculated (Figure 6c) temperature profiles near injection wells show a consistent reverse "S" pattern, suggesting the occurrence of thermal convection; hot water moves along the upper portion of the aquifer while cooler water sinks and moves along the lower part of the aquifer. A two-dimensional convective flow field, as shown in Figure 6c, is superimposed on the temperature field, demonstrating the alteration of the conductive field by convection. The greatest alteration occurs in the permeable Salado ore zone, as a result of active movement of ground water, while purely conductive thermal fields dominate in the overlying confining unit.

The current thermal mining in the northwest section of the ore body begins on the up-slope of an inclined ore body and gradually proceeds down-slope. A series of simulations reveal the potential heat transfer pattern of this mining approach (Figure 7). Figure 7a shows the thermal injection starting on the top of the inclined layer. The predicted small cone of depletion indicates a significant loss of heat through the thin cap rock, as shown in the case of the anticline (Figure 3a). As the thermal mining proceeds down-dip, simulations show that most of the hot fluid migrates, by buoyancy, up-slope where the porosity and permeability of the formation has been enhanced by sulfur extraction, rather than migrating down-slope toward the target mining area (Figure 7). For simulations, the permeability of the depleted ore zone was increased from 10^{-2} darcy to 1 darcy, due to sulfur extraction. Significant amounts of heat can also escape upward through fractures developed by subsidence in the overlying confining unit (Figure 7d). Fracture development and land subsidence are common at the mining site where overburden collapses into the underlying depleted ore zones. These modeling results demonstrate how heat migrates up-slope where permeability is enhanced by mining, which explains why the production rates decrease rapidly as the mining gradually proceeds down-slope.

The modeling results provide an opportunity for the evaluation of potential heat transfer processes during thermal mining operations. Independent field temperature data are consistent with the modeling predication that thermal injection drives convective motion of fluids in inclined and folded geologic formations. Although simple heat transfer calculations of Rayleigh numbers (Domenico and Schwartz 1997) may yield the same conclusion on the occurrence of thermal convection, numerical models were used in this study to examine how geologic structures may affect the efficiency of thermal mining, including controls on direction of heat transfer and the size of the cone of depletion. Those modeling results are useful in the search for an optimum mining strategy for thermal mining within various geologic settings.

Conclusions

Numerical modeling in combination with field data can provide a powerful tool for quantitative evaluation of heat transfer processes associated with thermal mining operations. Simulations of coupled heat transfer and variable-density ground water flow indicate that thermal injection creates a lateral temperature gradient and drives a convective motion of ground water. The occurrence of thermal convection is convincing considering the "S" pattern of highly disturbed conductive temperature profiles observed in injection zones. The model demonstrates how inclined, folded, and fractured geologic structures may affect heat transfer during thermal mining operations. The dominant heat dissipation of the current mining operation appears to be convective or buoyant transport along the up-dip of inclined beds or through fractured confining clay layers overlying the ore zones. The up-dip dissipation of heat results in low recovery and production rates as thermal mining proceeds down-slope along an inclined ore zone.

Further research should be directed toward numerical and field tests to identify alternative approaches to improving recovery efficiency. Increasing the density (salinity) of the injection water could provide negative buoyant forces and enhance the down-dip migration of hot water. The approach, however, may require the redesign of water treatment/processing systems because hot saline water is highly corrosive to water transportation and storage facilities. Additional computer simulations should be performed to evaluate new mining strategy; such as thermal mining at the bottom of the inclined ore zones and proceeds up-dip. In addition, geochemical modeling regarding the mixing of hot and cold ground water should be of prime importance for understanding anticipated geochemical problems, such as electrochemical/galvanic corrosion and well/pipeline clogging by mineral precipitation or microbial growth.

Acknowledgments

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References

Bethke, C.M., M.-K., Lee, H. Quinodoz, and W.N. Kreiling. 1993. *Basin Modeling with Basin2, A Guide to Using Basin2, B2plot, B2video, and B2view*. Urbana, Illinois: Hydrogeology Program, University of Illinois.

Blanchard, P.E., and J.M. Sharp Jr. 1985. Possible free convection in thick Gulf Coast sandstone sequences. Southwest Section AAPG 1985 Transactions. Tulsa, Oklahoma: American Association of Petroleum Geologists: 6-12.

Buscheck, T.A., C. Doughty, and C.F. Tsang. 1983. Prediction and analysis of a field experiment on a multilayered aquifer thermal energy storage system with strong buoyancy flow. *Water Resources Research* 19, no. 5: 1307-1315.

Crawford, J.E., and C.S. Wallace. 1993. Geology and mineralization of the Culberson sulfur deposit. In *New Mexico Geological Society Guidebook*, 44th Field Conference, Carlsbad Region, New Mexico and West Texas: 301-316. Socorro, New Mexico: New Mexico Geological Society.

Davis, S.H., S. Rosenblat, J.R. Wood, and T.A. Hewett. 1985. Convective flow and diagenetic patterns in domed sheets. *American Journal of Science* 285, no. 3: 207-223.

Domenico, P.A., and F.W. Schwartz. 1997. *Physical and Chemical Hydrogeology*, 2nd ed. New York: John Wiley and Sons.

Hanor, J.S. 1987. Kilometer-scale thermo-haline overturn of pore water in the Louisiana Gulf Coast. *Nature* 327, no. 11: 501-503.

Hill, C.A. 1996. *Geology of the Delaware Basin, Guadalupe, Apache, and Glass Mountains, New Mexico and West Texas.* Society of Economic Paleontologists and Mineralogists Special Publication 96-39. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists.

Lee, M.-K. 1997. Predicting diagenetic effects of groundwater flow in sedimentary basins: A modeling approach with examples. In *Basinwide Fluid Flow and Associated Diagenetic Patterns: Integrated PetroGraphic, Geochemical, and Hydrologic Consideration*, ed. I.P. Montanez, J.M. Gregg, and K.L. Shelton. Society of Economic Paleontologists and Mineralogists Special Publication 57: 3-14. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists.

Ludvigsen, A., E. Palm, and R. McKibben. 1992. Convective momentum and mass transport in porous sloping layers. *Journal of Geophysical Research* 97, no. B9: 12315-12325.

McKenna, T.E., and J.M. Sharp Jr. 1998. Radiogenic heat production in sedimentary rocks of the Gulf of Mexico basin. *American Association of Petroleum Geologists Bulletin* 82, no. 3: 484-496.

Molz, F.J., J.G. Melville, A.D. Parr, D.A. King, and M.T. Hopf. 1983. Aquifer thermal energy storage: A well doublet experiment at increased temperatures. *Water Resources Research* 19, no. 1: 149-160.

Phillips, S.L., A. Igbene, J.A. Fair, and H. Ozbek. 1981. A technical databook for geothermal energy utilization. Lawrence Berkeley Laboratory Report LBL-12810. Berkeley, California: Lawrence Berkeley Laboratory.

Raffensperger, J.P. 1997. Evidence and modeling of large-scale groundwater convection in PreCambrian sedimentary basins. In *Basinwide Fluid Flow and Associated Diagenetic Patterns: Integrated Petrographic, Geochemical, and Hydrologic Consideration,* ed. I.P. Montanez, J.M. Gregg, and K.L. Shelton. Society of Economic Paleontologists and Mineralogists Special Publication 57: 15-26. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists.

Wilson, E.N., L.A. Hardie, and O.M. Phillips. 1990. Dolomitization front geometry, fluid flow patterns, and the origin of massive dolomite: The Triassic Latemar buildup, Northern Italy. *American Journal of Science* 290, no 7: 741-796.