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Full length research paper

Simulation of ionic transport for estimation of hydraulic conductivity by history matching electric log measurements with Modflow and MT3D

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It was found that the hydraulic conductivity (permeability) of a formation could be estimated by history matching the invasion of a known mud filtrate into a known water quality (resistivity) of an aquifer. A drilled well is modeled, varying permeability, in a reservoir simulator until the invasion parameters of a contaminant transport model matches the resistivity curves made on an electric well log for a given set of data.

Abbreviations: TDS = total dissolved solids; ppm = part per million or mg/l; ohmm = ohm meter; mho = seimens; SI Metric Conversion Factors; ft x 3.048; E-01 = m; ft^2 x 9.290 340 E-02 = m^2; ft3 x 2.831 685 E-02 = m3; bbl x 1.589 873 E-01 = m3; gal x 6.677 467 E+01 = m3; acre x 4.046873 E-01= ha;

INTRODUCTION

A new method of estimating hydraulic conductivity (permeability) was determined in studying the Ojo Alamo Aquifer of northwestern New Mexico (Russell, C, 2008). A reservoir simulator is run with a contaminant transport program varying the permeability until the electrical conductivity of the borehole matches the electrical conductivity read on well logs for the assumed hydraulic conductivity. The model assumes that all needed input parameters are known except for the hydraulic conductivity. This is the case of the Ojo Alamo Aquifer in most instances.

The models herein were made with Modflow written by Shapiro, et al, (1997), a commercial hydraulic flow program and MT3D (Zheng C 1990) a commercial contaminant transport flow model. Both of these programs are free software and supported by the USGS. However, any reservoir simulator with particle tracking capabilities could be used.

METHOD

It was found that the permeability of a formation could be determined from a set of resistivity curves across that formation given:

1. Invasion of the mudfitrate has not completely passed the diameter read by the deepest reading resistivity measurement,
2. The hole has been drilled predominately with water (no gel) and permeability has not decreased dramatically due to solids buildup on the borehole,
3. Time of contact between the formation and the drilling fluid,
4. Resistivity or ion concentration of the drilling fluid and formation water,
5. Formation and borehole head and
6. Formation porosity.

The process that has proven to provide an estimate of permeability, within an order of magnitude, is as follows:

1. Build a Modflow model that represents the borehole and surrounding conditions,
    A. Represent the borehole as a constant head:
        a. Borehole head equals depth at point of measurement multiplied by specific gravity of drilling fluid (partial data on log header),

B. Provide the formation head or an accurate estimate,
C. Provide the formation storage coefficient or an accurate estimate,
D. Grid the system to reflect the conditions,
a. The borehole is centered in the grid,
b. The region surrounding the borehole is divided sufficiently to provide data at the areas corresponding to the measured resistivities,
c. The outside boundaries of the grid may be active or sufficiently large whereby reservoir boundary effects may be neglected,
E. Assume a transmissivity and run Modflow under transient conditions since the near wellbore pressure will be changing with time as borehole fluid invades the aquifer.

2. Build as MT3D contaminant transport model that represents the borehole and surrounding conditions,
A. Input porosity of the formation as found on the density or neutron log or as estimated from the formation resistivity factor,
B. Input the ion concentration of the borehole drilling fluid and represent this as a constant source term, you may choose to use the conductivity (resistivity) of the mudfiltrate (data on log header) instead of the concentration,
C. Input the initial ion concentration of the formation water; you may choose to use the conductivity (resistivity) of the fluid instead of the concentration,
D. Run MT3D with the output data from the previous Modflow simulation. Note: the upstream finite difference approximation appears to give a valid solution in that the concentration distribution in the output is in the form of concentric circles. The more advance solution techniques may show bizarre concentration distributions.

3. Compare MT3D output with measured resistivity curves. If output does not match the measured resistivity curves, then assume a new transmissivity and rerun the Modflow model and the MT3D model until a match is secured. The MT3D data that matches the resistivity curves will represent the best estimate of the hydraulic conductivity.

EXAMPLE RESULTS

The process described above was used to estimate the transmissivity of a sandstone layer located in the Mission Federal #1, a wildcat drilled in Sec 15, Twp 24N, Rge 10W of the San Juan Basin, in northwestern New Mexico. The Ojo Alamo portion of the electric log and log header are herein. A storage coefficient of 0.001 was assumed based on local data. The results show a transmissivity of 0.25 ft^2/hr matches the invasion of the mudfiltrate as characterized by the resistivity log readings at 24” and 60”. This transmissivity is translated to a hydraulic conductivity of 2.31e-6 ft/sec. Average overall conductivities as calculated from actual pumping tests in the Ojo have shown to be 2e-5 ft/sec while isotopic studies estimate overall conductivities in the low micrometer/sec range per Phillips & Tansey (1984).

The sandstone interval from 710’-740’ measured showed the widest variation in resistivity measurements at 24” and 60”, and thus may be assumed to have the poorest conductivity in the Ojo Alamo interval of this particular well. The current study has shown better comparison to the norm (2e-5 ft/sec) using this process on other wells. The present case is presented as an introduction to the methodology, whereby input data was reliably estimated and not skewed to fit the expected hydraulic conductivity.

An electric log of the Mission Federal #1 shows the Ojo Alamo sandstone interval from 640’ to. The interval shows three distinct sandstones separated by thin shales at approximately 710’ and 740’. The transmissivity for the intermediate sandstone interval from 710’ to 740’ will be estimated using the aforementioned process.

Data Evaluation - Conductivity of the Invaded Zone Fluid, Mudfiltrate, and Formation Water

MUD FILTRATE WATER PROPERTIES

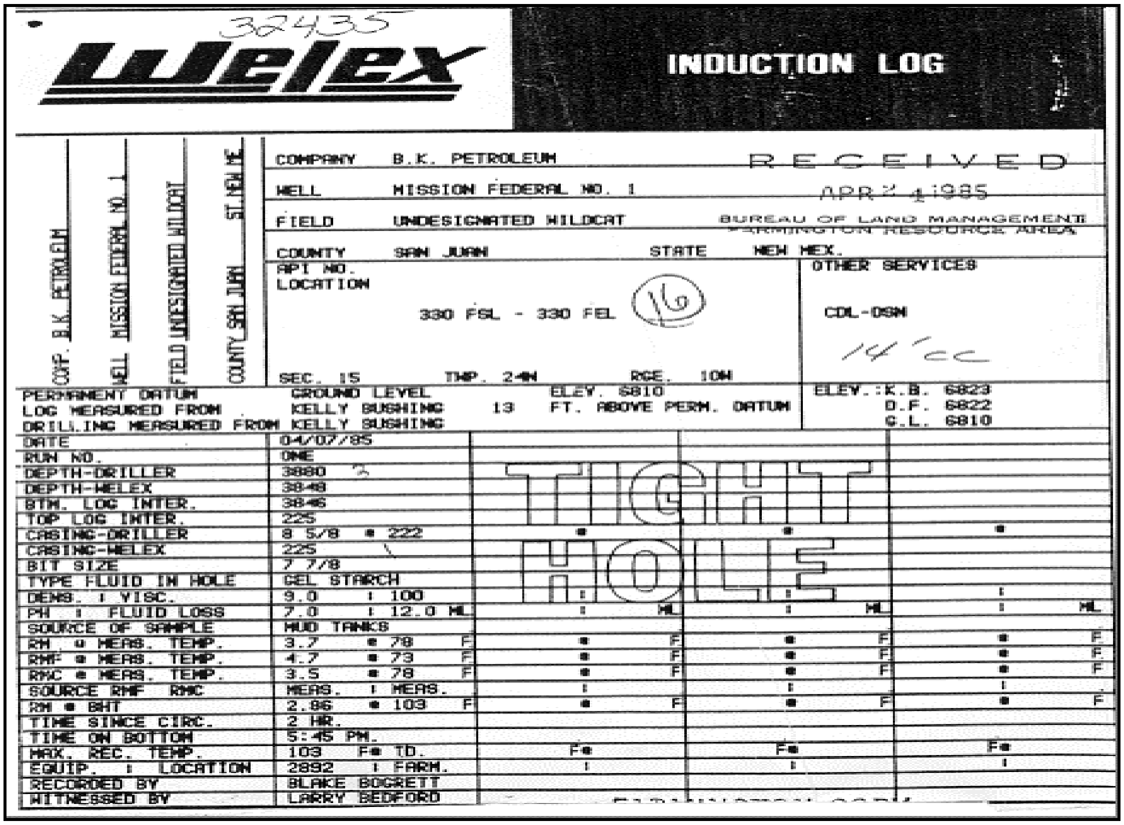
Conductivity

In order to find the level of invasion, the insitu and mud filtrate water properties must be evaluated. Since the log header (Figure 1) gives the resistivity of the mud filtrate, this is used to quantify it’s water quality or electrical conductivity at formation temperature.

The deep resistivity reading from 710’-740’ is greater than the short guard reading. Considering homogeneity in the near wellbore region, this would signify the formation water contains less ions than the mudfiltrate. If it is assumed that the mudfiltrate has invaded the near wellbore region to a horizontal depth of 24”, then the short guard reading would signify only that resistivity of the formation and the mudfiltrate. The short guard (SG) induction device has a focused horizontal measuring capacity of 24”. The SG reading averages approximately30 ohm-m in this region. This resistivity is a sum of the resistivity of the formation and the pore water. A formation resistivity factor may be calculated for this interval from the relationship:

$$F = \frac{Rs}{Rmf}, F = \frac{30}{4.26} \quad (1)$$

Where: F = the formation factor; Rs = the shortest focused resistivity measurement (ohm-m); Rmf = the mudfiltrate resistivity at depth corrected for temperature (ohm-m)



32435

Welex — INDUCTION LOG

COMP. B.K. PETROLEUM
WELL MISSION FEDERAL NO. 1
FIELD UNDESIGNATED WILDCAT
COUNTY SAN JUAN ST. NEW ME.

RECEIVED APR 24 1985 BUREAU OF LAND MANAGEMENT FARMINGTON RESOURCE AREA

COMPANY	B.K. PETROLEUM
WELL	MISSION FEDERAL NO. 1
FIELD	UNDESIGNATED WILDCAT
COUNTY	SAN JUAN STATE NEW MEX.
API NO.	
LOCATION	330 FSL - 330 FEL (16)
SEC. 15	TWP. 24N RGE. 10W
OTHER SERVICES	CDL-DSN 14'cc

PERMANENT DATUM GROUND LEVEL ELEV. 6810
LOG MEASURED FROM KELLY BUSHING 13 FT. ABOVE PERM. DATUM
DRILLING MEASURED FROM KELLY BUSHING
ELEV.: K.B. 6823 D.F. 6822 G.L. 6810

DATE	04/07/85
RUN NO.	ONE
DEPTH-DRILLER	3880
DEPTH-WELEX	3848
BTM. LOG INTER.	3846
TOP LOG INTER.	225
CASING-DRILLER	8 5/8 @ 222
CASING-WELEX	225
BIT SIZE	7 7/8
TYPE FLUID IN HOLE	GEL STARCH
DENS. : VISC.	9.0 : 100
PH : FLUID LOSS	7.0 : 12.0 ML
SOURCE OF SAMPLE	MUD TANKS
RM @ MEAS. TEMP.	3.7 @ 78 F
RMF @ MEAS. TEMP.	4.7 @ 73 F
RMC @ MEAS. TEMP.	3.5 @ 78 F
SOURCE RMF RMC	MEAS. : MEAS.
RM @ BHT	2.86 @ 103 F
TIME SINCE CIRC.	2 HR.
TIME ON BOTTOM	5:45 PM.
MAX. REC. TEMP.	103 F@ TD.
EQUIP. : LOCATION	2892 : FARM.
RECORDED BY	BLAKE BOGRETT
WITNESSED BY	LARRY BEDFORD

TIGHT HOLE

Figure 1: Mission Federal #1 log header.

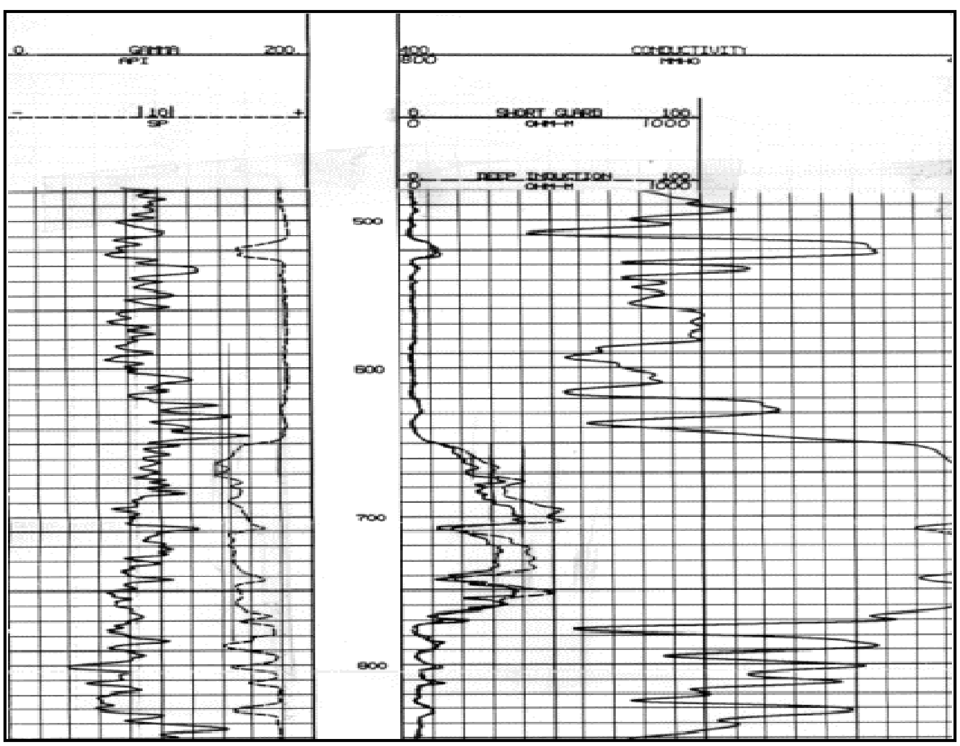


Figure 2: Mission Federal #1 SP, GR, SG, DIL – OAS 640' to 780'.

Equation 1 gives F = 7.04 for the Mission Federal. The Mission Federal's mudfiltrate resistivity was matched very closely with the value calculated from ion concentrations (4.66 compared to 4.7). Here it was considered 3 sacks of soda ash were added and the mix water was from a nearby Ojo Alamo water well. It was apparent that no caustic soda was added since the pH is listed as 7.0 on the log header. The concentration may be inferred from the resistivity measurements given an approximate ionic makeup. In both the mudfiltrate and the Ojo Alamo water, the principle ions are sodium, bicarbonate and sulfate.

Considering a homogeneous formation and that the mudfiltrate has totally engulfed the region measured as Rs, F may be considered a constant. For the present case the SG is used but a shallower log reading would be more preferable.

Since the formation factor is considered constant in the case of a isotropic formation, then the resistivity of the water at the investigative depth of the deep tool may be ascertained where (Schlumberger, 1988):

$$Rxo = \frac{Rd}{F}, \ Rxo = \frac{42}{7.04}$$

Equation 2

Where: Rd = the deepest focused resistivity measurement (ohm-m)
Rxo = the fluid resistivity in the invaded zone corrected for temperature (ohm-m)
F = formation factor

For the Mission Federal, Rxo = 5.97 ohm-m. This fluid resistivity at 60" (Rxo) corresponds to a conductivity of 0.1675 mho/m. Having defined the conductivity of the mudfiltrate and that of the fluid held in the region surrounding a horizontal depth of 60" from the wellbore, the formation water conductivity is needed. This electrical conductivity may be estimated from data collected from surrounding Ojo Alamo wells. Brimhall (1973) and Stone (1983) define the ionic make-up of this local Ojo Alamo water in their work. From the calculations it is found that:

Cw = 0.1022 mho/m
Cdeep = 0.1675 mho/m
Cmed = 0.2344 mho/m

Where: Cw = the Ojo Alamo formation water conductivity
Cdeep = the fluid conductivity at the depth measured by Rd
Cmed = the fluid conductivity at the depth measured by Rs

In this example formation water ionic strength is converted to conductivity (Russell, C, 2008). The conductivity is measured here such that the well may be modeled as a mass source and not a sink as would be portrayed in the event resistivity was used. Concentration could also be used in the model.

Porosity

Often the porosity may be determined from a density or neutron log directly. However for the Mission Federal 1, a porosity log is not available.

The porosity of the Ojo Alamo is measured as 22% in two nearby wells. This data is found in works by Brimhall (1973) and Stone (1983). In this same study, the porosity of the Ojo Alamo was calculated for nineteen wells and the resultant mean was 20%. A porosity of 20% was used for the interval.

Head

The initial heads used in the model reflects area data as found in the works by Brimhall (1973) and Stone (1983). The head in the wellbore was calculated from data found on the log header in Figure 1.

Contact Time

Time of occurrence is estimated from personal experience. Typically in the San Juan Basin a well of this depth is drilled in three to four days. The estimated time interval between the mud-up procedure and the penetration of the Ojo Alamo is 52 hours. This includes trip time. It is further estimated that 10 hours progressed from the time mud-up starts to the end of circulation prior to the trip out of the hole for logs. The 52 hours represents stress period number 1 while the 10 hours represents stress period number 2. Stress period number 1 is characterized by head build-up in the Ojo Alamo without ion invasion. Here, it can be shown that the drill water and the insitu water are the same. The second stress period is characterized by further head build-up in the near wellbore region and invasion by the mudfitrate. The permeability of the formation is assumed unchanged during drilling and circulating activities. This assumption is based on that minimal wallcake is made during circulation with upward velocities of 100 – 150 fpm and that a boundary layer of water is maintained across the formation until the first trip is made after the hole is mudded up. After stress period number 2, there is an additional 5 hrs that transpires as the Ojo Alamo interval is logged. This period of time is not included due to formation of mudcake and radically decreasing permeability during this noncirculating phase.

Modeling/History Matching

Using the above defined parameters, a transmissivity was assumed and the Modflow/MT3D model was run.

The electrical conductivity output from this model was then compared to the electrical conductivities calculated from the well logs at 24" and 60" into the formation. When the resultant model electrical conductivities match the well log electrical conductivities, the associated transmissivity is considered the best estimate.

The borehole is represented as a constant head with conductivity somewhat larger than the transmissivity guess. Future models may use the borehole conductivity as skin source so that wallcake build-up may be inferred. A basic backwards in time linear regression technique is used for particle tracking. The method is unsophisticated but quick and results in a homogeneous particle distribution. No diffusion is allowed for. Ionic flux would be expected at e-9 ft^2/s and thus insignificant at the short time intervals modeled.

The present model uses a 41 x 41 single layer grid with a progressive length differential in the grids. The overall length is 11,111 feet with a centered wellbore. This large scale preempts any boundary effects. A semi-steady state solution is allowed for near wellbore head changes with time.

Conclusion for Hydraulic Conductivity Estimate Procedure

The above method of estimating conductivity is good but having first hand knowledge of the drilling environment and conditions would prove more reliable. This includes having available the EC for the OAS water and mudfiltrate. Also a set of three resistivity curves (short, medium, and deep) would improve the accuracy in addition to a porosity log.

Definitions of Terms

Advection – Transportation by horizontal movement; Bentonite – A clay added to drilling mud to increase the carrying capacity of the mud. Also called gel; Compensated Neutron Log (CNL) – The CNL emits neutrons from a radioactive source, which collide with the rock in the wellbore. The porosity of the rocks can be determined by the amount of neutrons that are received back to the CNL tool; Hydraulic Conductivity – The ability of rock to carry water; Conductivity of ions – The ability of ions to carry an electrical charge; Drilling Mud – Fluid used in drilling to transport drilled rock cuttings to the surface.

Electric Logs – Tools used in measuring properties in wellbores; Electric Survey (ES) – The electric survey consists of 16 inch normal, 64 inch normal, and 18' 8" lateralog. These are all resistivity logs that measure resistivity in the wellbore; Electrical Conductivity (EC) – The ability of water to conduct electricity with the presence of ions; Formation Density Log (FDL) – The FDL emits medium energy gamma rays into the formation. The porosity of the formation may be determined by the amount of gamma rays that are returned to the source; Formation Pressure – The pressure in a formation caused by overburden, gas expansion, and hydrostatic head; Formations – Strata containing multiple types of sedimentary layers; Homogeneity – All of one characteristic; Hydrostatic Head – That pressure exerted by a column of water; Invaded Zone (xo) – That portion of the wellbore completely containing drilling fluid; Ionic Strength – A method of taking into account the varying effects of ionic charge; Ionic Diffusivity – The transfer of ions in the absence of bulk flow; Ions – An atom or group of atoms, which has either an excess of deficient of electrons and is thus electrically charged; Lateralog – A focusing electrode tool that has less tendency to be affected by adjacent beds; MT3D – A particle transport program; Mud Cake (MC) – The layer of mud that packs onto the wellbore;Mud Filtrate (MF) – The water and dissolved solids contained in the drilling mud; Modflow – A fluid-modeling program;Ojo Alamo Sandstone (OAS) – An aquifer found in the San Juan Basin at approximately 3000'; Permeability – The ability of rock to transport water; Porosity – Void space contained in rock; Resistivity Log – In conventional resistivity logs currents are passed through the formation via certain electrodes and voltages are measured between certain others.

Resistivity of Water (RW) – The resistivity of insitu water that may be determined by certain relationships derived from resistivity log measurements.

San Juan Basin – A geologic basin located in northwestern New Mexico.

Shale – A fine-grained sedimentary rock formed in a sea environment.

Soda Ash – A drilling mud additive used to increase the volume of the bentonite.

Total Dissolved Solids (TDS) – Those solids found dissolved in water, which may include petroleum products and ions.

Transition Zone – That zone in the wellbore containing in situ fluids and drilling fluids.

Transmissivity – The ability of rock to carry water for a given height of rock.

Viscosity – The property whereby a fluid resists flow.

Water Loss Additive – A portion of the drilling mud that seals off the formation to present drilling mud invasion.

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