Manual for SAGD Proxy Modeling Software with an Example

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A program was written for ranking SAGD well pair models. This program is based on approximate simulation of entire process using a semi analytical model based on the Butler's SAGD theory. This tool used this theory as a basis, but for better predicting oil and steam production, some calibrations should be done for improving efficiency of this method. As a result, this tool can be calibrated automatically for finding better match between results of simulator and proxy. Also this tool can be used for short and long term prediction of production.

Introduction

Butler's theory is based on the predicting steam chamber location and amount of oil production at different locations and different time steps. This method works only for $2D$ sections. For considering $3D$ sections, the interaction between different slices is neglected, and then amount of oil or steam production for different slices should be summed together for finding cumulative oil or steam production. This method works based on the location of production well. Location of injector is not important in this model, but by considering steam pressure the rate of heat penetration to the reservoir can be controlled. Fig. 1 shows how Butler's model can convert a 3D model to different $2D$ sections.

This model assumes two different periods for oil production: 1-Rising period 2-Spreading period. Rising period assume steam can migrate to the top of reservoir and after that during spreading period steam moves toward the boundary of reservoir. Most of the times, steam chamber in proxy moves faster than reservoir simulator. This can cause front reaches to the boundary much faster than simulator and it causes wrong prediction for different periods. For controlling front speed, Butler suggested to decrease the steam pressure (Bulter 1987; Butler, 2000). In this code, steam pressure can be adjusted automatically for preventing this problem.

Butler's theory cannot predict amount of steam production and as a result CSOR. For this reason, Rose's theory can be used for predicting amount of steam production at different time steps. Amount of steam at different time steps can be predicted using the following formula (Rose, 1993):

$$\text{CSOR} = \frac{\text{total heat transferred/unit volume of oil}}{\text{enthalpy of steam/unit volume of water}} = \frac{(T_s - T_r)(C_r \rho_r Q_c^* + C_r \rho_r Q_r^* + C_o \rho_o Q_o^*)}{Q_c^* \Delta H_w \phi \Delta S_o}$$

In this formula, Q_c^* is cumulative heat to the steam chamber and produced oil from reservoir temperature T_r to steam temperature T_s, Q_r^* is cumulative heat to the reservoir, Q_o^* is cumulative heat loss to over burden above steam chamber, C_r and C_o are rock and overburden compressibility respectively, ρ_r and ρ_o are rock and overburden density respectively, ΔH_w is difference between enthalpy of injected steam and steam at the production line, ϕ is porosity and ΔS_o is difference between average oil saturation and residual oil saturation.

The proxy can be run for different purposes. In below you can see different options that we can select during running the proxy:

1- Calibrating proxy parameters using sequential quadratic programming (SQP)
2- Calibrating proxy parameters using simulated annealing method (Vanegas et. al, 2008)
3- Running proxy with optimized parameters for predicting oil and steam production
4- Calibrating proxy parameters using differential evolution optimization method
5- Calibrating proxy parameters using particle swarm optimization method
6- Ranking SAGD wellpair models by estimating net present value (NPV)

Between all optimization options you can see for calibrating proxy, SQP is the most robust and efficient method. This method is a gradient method based on estimating gradient and Hessian at each iteration and finding decent direction in the feasibility region for minimizing objective function which is mismatch between oil and team production rates of proxy and simulator. Fig. 2 shows a flowchart for finding the optimal solution using SQP optimization algorithm.

For solving a nonlinear optimization problem using SQP, it should be converted to the quadratic problem (QP) using approximation in Taylor series. First initialize the values of x (initial feasible solution) should be selected. Then QP problem should be solved for finding search direction. Step length can be obtained by minimizing merit function and after that initial solution can be updated by the following formula:

$$x_{k+1} = x_k + \alpha_k \delta_k$$

If decreasing in the objective function of two successive iterations is not significant algorithm will stop, otherwise procedure with new initial solution which is the updated solution should be continued till we find the optimal solution.

Other methods such as simulated annealing, differential evolution and particle swarm are based on generating a population and finding objective function for each of those cases and then improving the best of them in the iterative process. These methods are much slower than SQP, but as an advantage they will not stuck in local minimums and trying to find global minimum, but running time may be very large. Considering methodology of these methods and comparing them to each other is not objective of this paper.

Also ranking SAGD realization is a very important option in this tool. Realizations can be ranked based on their net present value (NPV). NPV can be obtained using the following formula:

$$NPV = \sum_{i=1}^{N_t} \frac{v_o Q_{oi} - v_w Q_{wi}}{(1+r)^{t_i}}$$

In this formula, i is time step index, N_t is total number of time steps, r is discount rate, t_i is cumulative time since start of production, v_o and v_w are price of oil and cost of steam production, Q_{oi} and Q_{wi} are total oil and steam production over the time step Δt_i. Using this formula, all of important factors can be considered.

Proxy program
This program is similar to the Gslib programs. Especially format of input data file is completely the same as Gslib format. Origin as all Gslib data files for gridded data is at the bottom left. Parameter file is pretty different from Gslib parameter files. There are many parameters in the data file, but the order of them is not important most of the time, although it is better to keep the order same as it is. Double star ** in each line of parameter file means that line is only comment for users and software will not read that line.

The last line of parameter file should be the ENDSET keyword and all of keywords after that will be skipped by program. In below you can see explanations for different lines of parameter file.

```
1  PRJNAME   '3D real model'
2  FILEPRE   $1_$2_$3_$4  ** Prefix used for output files
3  NSETS     1            ** Number of data sets used in the fitting process
4  SEED      929929.      ** Random number seed
```

On Line 1 you can set a name for project. On Line 2 a prefix can be set for debugging file. This can be useful when you have a script and you want to generate different files with different names. On Line 3 number of data sets can be set. When we like to calibrate proxy using several data sets, like P10, P20, …, P90 we can define number of data set in this line. On Line 4 random seed number can be set. This option is useful when we are using calibrating algorithms such as simulating annealing, differential evolution or particle swarm, but SQP does not need any random number for calibration.

```
5  TIMEFREQ 30.0      ** Frequency for reporting results, days
6  ENDTIME  5400.0    ** Final time for producing the wells, days
7  MINTIME  1000.0    ** Minimum time for producing the wells, days
```

On Line 5 frequency for reporting results can be defined. This number should be the same as reporting frequency for STARS or any other simulator results. Final time step (days) can be set on the Line 6. Also minimum time for

producing from well can be defined on Line 7. After that if water cut is greater than 0.95, well will be shut automatically and all production or injection rates set to the zero.

```
 8  AFR        0  1.0   2.5    ** Adjusting factor for rising period
 9  AFS        0  1.0   2.5    ** Adjusting factor for spreading period
10  PERMF      0  1.0   1.5    ** Adjusting factor for averaging permeability
11  AFCSOR     0  $3    2.5    ** Adjusting factor for csor
12  AFPRESS    0  1.0   2.5    ** Adjusting factor for steam chamber pressure
```

In this case, five different factors have been selected for calibrating proxy. Basic Butler's theory cannot predict rates very well and for predicting oil and steam rates, proxy should be calibrated with simulator results. For this reason these factors have been selected for this version of software. These five factors can be set on Lines 8-12. AFR and AFS are calibrating parameters for oil production during rising and spreading periods. PERMF is for calibrating average of permeability for each time step. Using this factor geomechanical effects as a result of changing permeability by changing reservoir temperature can be considered. AFCSOR is a factor for calibrating CSOR by changing enthalpy difference between steam inside the reservoir and steam at the production line. Finally AFPRESS is a factor for calibrating steam injection pressure. In this proxy, most of the times steam chamber moves faster than steam chamber in the reservoir simulator. For this reason Butler (1987) suggested that steam pressure should be decrease for preventing quick steam chamber movement. There are three different values in front of each of these factors. Second and third ones are the constraints of each factor. For simulated annealing method, first value can be cause different values for the second and third columns. First value is option for generating population from specific distribution. All of these distributions have two values except uniform distribution (constant) which has one value and triangular distribution which has 3 values. In below you can see what the next columns are by choosing the first value:

0 for constant   (cte)
1 for uniform   (xmin,xmax)
2 for triangular (xmin,xmod,xmax)
3 for normal   (xmean,xst)
4 for lognormal   (xmean,xst)

For example if the first value is 1 (uniform distribution) the second and third values are minimum and maximum values. Also if first value is 3 (normal distribution), the second and third values are mean and standard deviation for that normal distribution.

```
13  OPTMODE    1      ** Program mode (1: SQP   2: Simulated annealing   3: No fit   4:DE   5:PS   6:Ranking)
14  PERTURB    0.001  ** initial perturbation for gradient computation
15  OPTINDEX   1 1 1 1 1    ** index for optimization variables in the order of  (AFR,AFS,PERMF,AFCSOR,AFALPHA) -- 0:No, 1:Yes
16  CONVFAC    0.5    ** Convergence factor
17  ITMAX      100    ** Maximum number of iterations in each temperature level
18  MISAN      10.0   ** Parameter used to find the initial number of perturbations K=Mi*Ns (Ns number of parameters to adjust)
19  NPADJ      3      ** Number of parameters to adjust
20  X0         0.8    ** Desire ratio of accepted perturbations to calculate T0
21  TOLER      0.01   ** Tolerance (fraction), criterion to finish simulation
22  MINACRAT   0.1    ** Minimum acceptance ratio, criterion to finish simulation
```

On Line 13 you can set the program mode. If we just want to run the code for predicting the oil and steam production, mode 3 should be selected and calibrating values can be set in the second column on the lines 8-12. Also options 1, 2, 4 and 5 are for calibrating the parameters using sequential quadratic programming (SQP), simulated annealing, differential evolution (DE) and particle swarm (PS) respectively. Option 6 can be used if the code should be used for ranking reservoir realizations. Lines 14-15 can be used for SQP calibration method. On Line 14 perturbation parameter can be selected for computing gradients. This value should not be very small or very large because objective function is highly nonlinear and if this value is very small, algorithm will stuck on the local minimums. 0.001 is a reasonable assumption for perturbation parameter. On Line 15 we can define which parameters should be used for calibration. 1 means that parameter should be in the calibration and 0 shows that parameter should not participate in the calibration process. Lines 16-22 can be used for calibration using the simulated annealing method. Between all of calibration methods, SQP is the best and most efficient of them.

```
23  RANKFL    D:\script\Geology\rank.dat    ** if OPTMODE=6
24  NRANK     100            ** number of realizations for ranking
25  OILP      500      ** Oil cost per m3
26  WATERP    30       ** Steam cost per m3
27  DISCOUNT  0.1      ** Discount rate per year
```

If program mode is 6 (ranking realization) on Lines 23-27 ranking parameters and files can be defined. On Line 23 the file path of different geological models can be set. Format of this file is the same as Gslib format. In below you can see an example for this file:

```
Ranke file names
1
file names
100                      /number of realizations
D:\script\Geology\gslib\datafile_001.out
D:\script\Geology\gslib\datafile_002.out
D:\script\Geology\gslib\datafile_003.out
D:\script\Geology\gslib\datafile_004.out
D:\script\Geology\gslib\datafile_005.out
D:\script\Geology\gslib\datafile_006.out
D:\script\Geology\gslib\datafile_007.out
D:\script\Geology\gslib\datafile_008.out
D:\script\Geology\gslib\datafile_009.out
D:\script\Geology\gslib\datafile_010.out
D:\script\Geology\gslib\datafile_011.out
```

Each of these files has a format such as the below figure:

```
Geologic data file
7
Rock type
Horizontal permeability (md)
Vertical permeability (md)
Porosity
Oil saturation
Viscosity table number
Relative permeability table number
1    7438.060   6396.732   0.358   0.942   7.000  1
2       0.001      0.000   0.000   0.000   7.000  2
2       0.001      0.000   0.000   0.019   7.000  2
2       0.001      0.000   0.172   0.423   7.000  2
2       0.001      0.000   0.000   0.061   7.000  2
2       0.001      0.001   0.000   0.075   7.000  2
1       0.811      0.373   0.000   0.883   7.000  1
1    2692.715   2315.735   0.327   0.877   7.000  1
1       0.128      0.059   0.000   0.884   7.000  1
1    3102.134   2667.836   0.301   0.903   7.000  1
1     417.293    191.955   0.243   0.884   6.000  1
1    3606.693   3101.756   0.381   0.910   6.000  1
2       0.001      0.000   0.081   0.000   6.000  2
```

Geological file has 7 different columns and the format is the same as format of Gslib files. Number of data rows equal to the number of grids and the reference point is bottom left grid. On Line 24, number of realizations for ranking can be defined. Also on Lines 25-27 oil price/m3, steam production price/m3 and discount rate can be defined for computing net present value (NPV). Because most of the times ranking should be done based on the NPV and it is more reliable parameter compare to the oil production rate.

```
28  TRUEFL    D:\script\Geology\stars.dat
29  GEOLFL    D:\script\Geology\gslib\datafile_001.out  ** rocktype, Kh(mD), Kv(mD), porosity, So, visc table num, rel table num
```

If proxy should be used just for calibration, having simulator results is necessary. For this reason, format of simulator results should be changed based on the Gslib format. For this reason, time steps, oil rate (SC), cumulative oil rate (SC) and cumulative steam oil ratio are necessary. In below you can see an example for this file:

```
Data sc
4
TIME
Oil Rate SC
Cumulative Oil SC
Steam Oil Ratio Cum SCTR
  0    0            0            0
 30    1.230402589  10.35673332  313.866394
 60    2.416478396  41.37576675  113.1369019
 90    4.884603977  153.5690002  37.78559113
120   15.5007906   1069.175171   7.902053356
150   24.04785347  1797.324707   6.23978281
180   45.37050247  2773.051025   5.066616058
210   34.63308334  3915.008545   4.38057518
240   42.30607224  5047.834961   3.99181819
270   45.33763123  6437.140137   3.611858845
300   44.22853088  7790.046387   3.36969018
330   48.04502106  9236.90332    3.177477121
360   51.51016998  10809.31152   3.002045631
390   52.7766037   12385.71094   2.862172842
420   53.04180908  14017.77051   2.750083923
```

Also if we have a single (or multiple) models for calibration or a single model for prediction, the path of files should be defined on the Line 29 or after that respectively. Format is the same as geological files format for ranking.

```
30  NX         26           ** X grid definition
31  XSIZ       25.0           ** meters
32  NY         32           ** Y grid definition
33  YSIZ       2.5         ** meters
34  NZ         83           ** Z grid definition
35  ZSIZ       1.0           ** meters
36  NDISC      $1           ** Number of discritized grids in x direction (0=default value)
37  IWELLB     6   25      ** Well pair blocks in i direction
38  JWELLB     1   32         ** Well pair blocks in j direction
39  KWELLB     26  77         ** Well pair blocks in k direction
40  WELLDIR    'i'          ** well direction
41  NODES      D:\script\Geology\nodes.dat      ** x,y,z well coordinates
```

On Lines 30-35 the number of grids and grid increment in different directions can be set. In proxy we should discretize number of grids in the x and y directions. Number of grids in the y direction is always constant and it is equal to the number of grids in the simulator, but number of grids in the x direction is pretty sensitive and has effect on the final results, for this reason on the Line 36 you can change it as variable and check sensitivity of results by changing this value. 0 is a default value for this parameter. As we talked before, this proxy considers a box above the wells and center of this box can be the same for all of slices of a 3D model or it can be defined on the Line 41 by defining well trajectory file path. In the case of fix window, boundary of window can be defined on the Lines 37-39 and well is at the bottom-center of this box. In the case of variable window size for different slices, still boundary is the same as Lines 37-39, but well path is not at the bottom-center of this box and it can be defined by well trajectory in the trajectory files and path can be specified on Line 41. Also Line 40 can be used for defining well trajectory direction.

```
42  FANUM      2            **Number of facies
43  VISFLG     1            **Flag to use viscosity table file (VISCFL). if 0 it uses correlations
44  VISCNUM    1            **Number of viscosity tables
45  VISCFL     D:\script\Geology\visctable.dat
46  RESOS      0.23  0.21    ** Residual oil saturation for different facies, fraction
```

On Line 42 number of facies can be defined. Facies numbers should be started from 1 and facies 1 is sand and the last number is shale. On Line 43 we can define that PVT table or correlation should be used for calculating PVT properties. 0 means using correlation and one means using PVT table. Also if PVT table should be used, on Lines 44-45 number of PVT tables and the path of PVT tables should be defined. If there are multiple PVT tables, all of them should be stored in the same file after each other. On Line 46 residual oil saturation for different facies can be defined. Number of values should be equal to the number of facies.

```
47  TEMPR      11.4         ** Initial reservoir temperature, deg C
48  THNUM      7            ** Number of thermal rock types
49  THRESH     0.05  0.2  0.4  0.6  0.8  0.95      ** Number of shale volume thresholds (should be THNUM-1 values)
50  THCONR     6.56E+05 5.99E+05 4.85E+05 3.71E+05 2.57E+05 1.44E+05 8.67E+04 ** Thermal conductivity of different rock types J/m.d.C
51  THCONW     5.68E+04        ** Water thermal conductivity, J/m.d.C
52  THCONO     9.27E+03       ** Oil thermal conductivity, J/m.d.C
53  THCOB      2.22E+05       ** Overburden thermal conductivity, J/m.d.C
54  ROCKCP     1.94E+06 1.96E+06 1.99E+06 2.02E+06 2.05E+06 2.08E+06 2.09E+06 ** Heat capacity of different rock types J/m3-C
55  CPOIL      2442.0       ** Oil fluid heat capacity, J/Kg-C    true=2442.0
56  CPOB       2.01E+06     ** Heat capacity of overburden, volumetric, J/m3-C
```

On Line 47 initial reservoir temperature can be set. On Line 48 number of thermal rock types can be defined. Thermal rock type number can be defined based on the volume of the shale (Computer Modeling Group manual). For this reason, volume of shale can be computed for each block based on the value of effective porosity, then using shale threshold thermal rock type number can be defined. For example, in this case there are 7 different thermal rock types. For this reason, 6 thresholds have been defined on Line 50. As an example if shale volume is less than 5%, that cell has thermal rock type number 1 and if shale volume is between 5%-20%, thermal rock type number is 2. On Line 50 thermal conductivity for each of these thermal rock types can be defined. Also on lines 51-53 water, oil and overburden thermal conductivities can be defined respectively. On Line 54 heat capacity of different thermal rock types should be defined. Finally oil fluid heat capacity and overburden heat capacity should be set on Lines 55-56.

```
57  API        8.5          ** Oil API density, deg  8.5
58  OILFVF     0.87          ** Oil formation volume factor
59  WRS        1.0           ** WOR/SOR for calculation fractional flow of water, fraction
```

On Lines 57-59 oil API density, oil formation volume factor and fraction of water oil ratio to steam oil ratio can be set. WRS value is usually equal to 1 and does not have too much effect on this version of program.

```
60  PRESS     $2   ** Steam chamber pressure, kPa
61  STEAMQL  0.90      ** Injeciton Steam quality, fraction
62  TEMPOUT   $4   ** Temperature of production fluids, deg C
63  STUPTIME  90.0     ** Start up time, days
64  ENDSET
```

On Line 60 steam chamber pressure should be set. Also steam quality should be set on Line 61. Temperature of production fluid should be set on Line 62. This value can be used for computing enthalpy of fluid at production line. If there is any startup period for steam injection, startup time can be defined on Line 63. All keywords after ENDSET on line 64 will be ignored.

Example

For case study, 100 synthetic $3D$ SAGD models (based on a realistic model) have been selected. These models have grid dimension of $26 \times 32 \times 83$. Grid size in x, y and z directions are $25\,m$, $2.5\,m$ and $1\,m$. There is pinchout at the bottom of the reservoir and also top water and top gas existed above the oil zone for all of them. 21 PVT regions existed for each of these models. Also 2 different facies existed in this reservoir with 7 different thermal rock types. Each facies has a separate relative permeability curve. Grids of the simulator model are corner point grids, but in this model we assumed grids are orthogonal and because in the corner point model all of grids (except grids at the pinchout) have pretty the same size, orthogonal model is a good assumption. Fig. 3 shows one of these models from top and also size of grids for one slice in the z direction. As you can see, grid size for all of grids in the z direction is 1.

Also Fig. 4 shows $2D$ facies model and well locations for one slice of one of these models along well direction. As you can see, well location is pretty at the center in the horizontal direction.

In this example, different sections have been considered separately. Then results of different sections added together for finding cumulative oil and cumulative steam rate.

In this study, proxy has been used for ranking reason. Most of the parameters and data files have been shown in the previous section. As we said before, thermal rock types can be defined based on the values of effective porosity for different cells. Fig. 5 shows a $2D$ map of thermal rock type numbers for one of these realizations. This computation can be done internally in the software and user does not need to enter thermal rock types to the model.

As a result, you can see all ranking results in a separate file with the name similar to the debug file name. Fig. 6 shows a sample of result file for ranking realizations. As you can see, you have different information about oil and steam production and computed NPV for each realization.

Running time for running proxy is about 40 seconds which is much smaller than the simulator running time which is about than 12 hours.

References

Butler, R. M., A New Approach to the Modeling of Steam-Assisted Gravity Drainage Journal of Canadian Petroleum Technology (JCPT), 1987.

Butler, R. M., GravDrain's Black Book: Thermal Recovery of Oil and Bitumen, Calgary, Albert, Canada, GravDrain Inc., October 2000.

Computer Modeling Group Ltd., STARS user manual, Calgary, Alberta, Canada.

Rose P. E., The Steam-Assisted Gravity Drainage of Oil Sand Bitumen. PhD thesis, Department of Chemicals and Fuels Engineering, The University of Utah, USA, August 1993.

Vanegas J. W., Deutsch C. V., Uncertainty Assesment of SAGD Performance Using a Proxy Model Based on Butler's Theory, SPE 115662, Presented at the 2008 SPE ATCE held in Denver, USA, 21-24 Sep 2008.
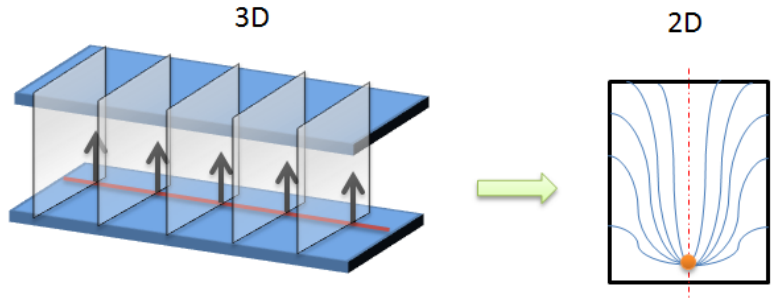
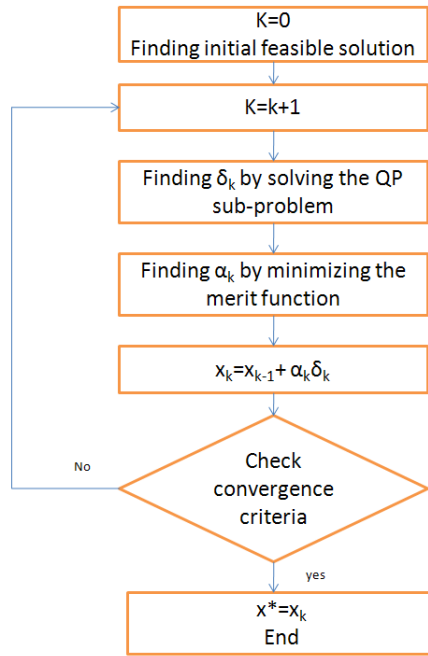**Figure 1**: Butler's model assumes no interaction between different slices in a $3D$ model

Figure 2: Flowchart for finding the optimal solution using SQP optimization algorithm
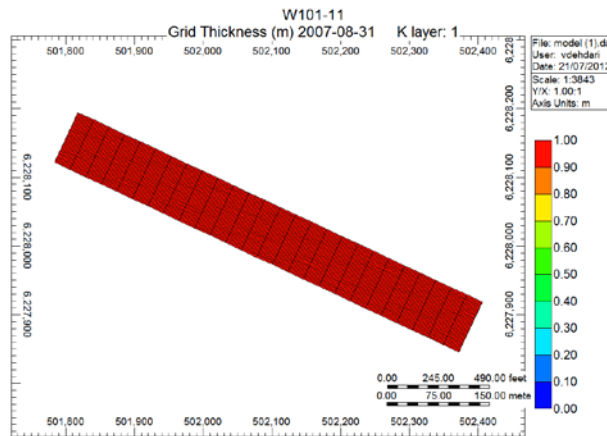

Figure 3: Model from top and also grid thickness for one slice in the z direction
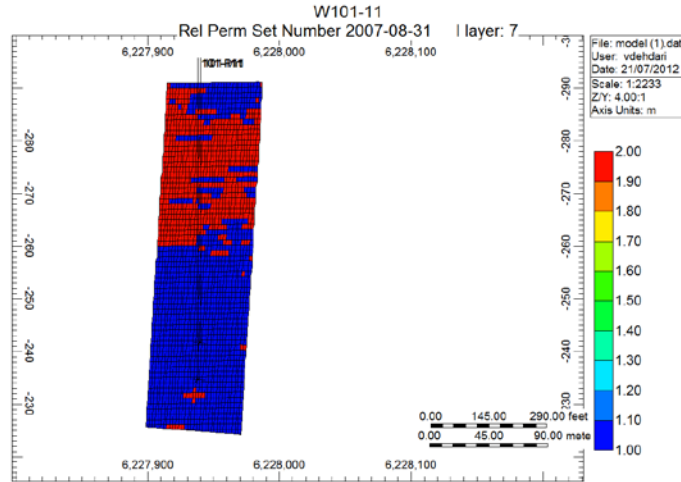
Figure 4: 2*D* facies model and well locations for one slice of model along well direction

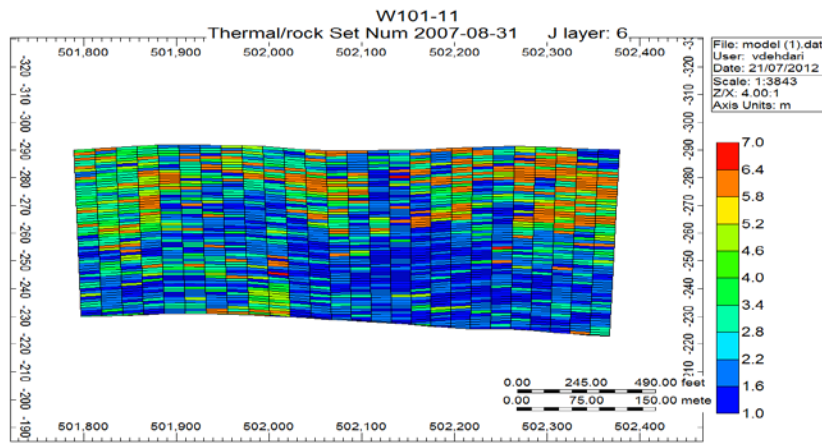**Figure 5**: 2D map of thermal rock type numbers for one of the realizations

```
Realization #      OOIP (RC)      OOIP (SC)          RF         Qo m3         Qw m3            NPV
          1       376943.844     327941.156        0.816    267479.875    2228548.750    43732900.000
          2       360152.562     313332.719        0.748    234435.766    2256236.750    33226884.000
          3       385221.000     335142.281        0.914    306291.969    2344651.000    55368628.000
          4       368968.125     321002.281        0.914    293346.000    2266548.750    52918184.000
          5       392792.562     341729.531        0.928    317088.125    2327952.250    58109916.000
          6       376334.062     327410.656        0.831    272039.625    2230837.250    45469520.000
          7       359834.781     313056.250        0.877    274447.844    2323402.500    44615272.000
          8       376666.219     327699.625        0.894    292950.688    2254885.750    54125648.000
          9       344634.906     299832.375        0.736    220824.562    2357059.250    26099822.000
         10       365492.938     317978.875        0.764    243050.375    2230148.500    36443952.000
```

Figure 6: Sample of result file for ranking realizations