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Static Connectivity Analysis of Low Sinuosity Channel Deposits, Cook Inlet, Alaska: A Conceptual Approach

Satyajit Mondal, Debasmita Misra and Abhijit Dandekar

ONGC Ltd., 4th Floor, INTEG GEOPIC, Dehradun-248165, Uttarakhand, India

Presenting author, E-mail: satyajit_mondal@hotmail.com

ABSTRACT

This study presents the results of static connectivity modeling of low sinuosity channel deposits (LSCDs) representing the Lower Sterling formation of Cook Inlet Region, Alaska. The overall objective was to understand the factors that control the probability of success (PS), static connectivity (SC) and effective static connectivity (ESC for 50 acre drainage area) in these LSCDs. This study illustrates a complete workflow from 3D grid construction to building of conceptual reservoir models using object based stochastic channel modeling technique to analyze PS, SC and ESC. The channel dimension data for the model construction was obtained from published South Clam Gulch Outcrop detail, Alaska Oil and Gas Conservation Commission (AOGCC) database, analog data and correlations for alluvial channels and LSCDs. The analyses were based on three channel datasets for three different sinuosities (1.1, 1.2, and 1.3). Each dataset was modeled for seventeen channel volume fractions and each with ten realizations resulting in 51 scenarios with 510 models. Fifteen vertical wells placed in different areas of the model were considered for the static connectivity analysis. In this analysis, different components of SC and ESC represent the mean SC and the mean ESC for one well only. From the analysis, it was found that at low channel volume, the PS, *as represented herein by the probability of one well intercepting channel facies*, is high for channel deposits of sinuosity of 1.2 and 1.3. However, channel deposits of sinuosity 1.1 show best ESC. For the channel volume approximately above 40%-45%, the SC and the PS are more than 90% for all sinuosities. It was also evident that approximately above 70% - 75% of channel volume, the role of channel dimension in static connectivity is limited and SC as wells as PS become 100% for all sinuosities. These results provide insights into the significance of channel dimension in the SC and ESC of low sinuosity channel modeling, which may also assist in predicting the factors that control the static connectivity of low sinuosity Tertiary gas reservoirs in Cook Inlet, Alaska.

INTRODUCTION

One of the primary factors that control high hydrocarbon recovery from a petroleum reservoir is connectivity. In a channelized reservoir, connectivity is of two types, viz. geobody or sandbody connectivity and reservoir-to-well connectivity (Larue and Hovadik, 2006). Geobody or sandbody connectivity is defined as the percentage of connected reservoir volume in the form of one or more sand bodies. The static connectivity (SC) is equivalent to "reservoir-to-well connectivity", which is defined as the volume of the reservoir connected to a single well or a group of wells. The goal of any reservoir modeling process is to understand the reservoir connectivity in static and dynamic conditions by integrating data from different sources. The SC is mainly controlled by the architecture of facies elements. Often, SC modeling involves many uncertainties due to incomplete data and a gap in our understanding the subsurface geology. Stochastic modeling techniques are widely used for quantification of uncertainty through the generation of many equiprobable models or realizations. Reliable static characterization of a geological model by a stochastic process is the cornerstone of the reservoir modeling process. Moreover the static reservoir characterization is helpful in understanding reservoir continuity, connectivity, and permeability architecture. In addition, static reservoir characterization can also be used in ranking geological models to be used for flow simulation studies and for understanding the geological factors that may play a significant role in the flow simulation process (Hovadik and Larue, 2007).

Many conceptual and outcrop based work that deal with SC of the channel sand bodies in relation to the net-to-gross ratio (Allen, 1978; Larue and Hovadik, 2006; Hovadik and Larue, 2007; Pranter and Sommer, 2011) are widely available. The model to analyze how the channel dimension controls the elements such as probability of success (PS) and SC for a particular drainage area and subsequent quantification, merits due importance and has been attempted in this research. Moreover, identification of the factors that control these elements is important for uncertainty and risk analysis in the exploration to appraisal and field development phase, which in turn helps in the decision-making and investment process.

The overall objective of this study was to build a series of conceptual - low sinuosity-fluvial stochastic models that were representative of reservoirs found in the Lower Sterling formation of Miocene-Pliocene age in the Cook Inlet Area. The scope of this research was to analyze the factors influencing the PS, ES and effective static connectivity (ESC) of these channel models with the hope that such analysis may throw light on future exploitation of tertiary gas formations in the Cook Inlet Region of Alaska.

Details of South Clam Gulch Outcrop

The Miocene/Pliocene Sterling Formation in Cook Inlet area mainly consists of a thick sequence of massive sandstones and conglomeratic sandstones with interbedded mudstone/siltstone and thin coals (Thomas et al., 2004). The overall depositional environment of the Sterling formation, on the basis of the outcrop study in the north and south Clam Gulch area as reported by Flores et al. (1997), represents low and high sinuosity fluvial channels within an alluvial-plain setting. As geologic time progressed, the low sinuosity streams evolved to high sinuosity streams during the deposition of Sterling Formation. The work of Flores and Stricker (1993) also concluded that the Lower Sterling Formation in the South Clam Gulch type section was formed by low sinuosity bedload streams.

In the Clam Gulch area, the Sterling Formation is of 2.25 mile (3.62 Km) long and north-dipping (Figure 1), which is exposed south and north of Clam Gulch area and oriented NE-SW (Flores et al., 1997). Flores et al. (1997) have studied that the channel sandstone units of the formation which occur as multistory and multiscoured bodies with internal scour bases that are locally marked by lag conglomerates. These units are 15–35 ft (4.57 – 10.67 m) thick with a lateral extent of more than 2000 ft (609 m).

METHODOLOGY

Procedure of Static Connectivity Modeling

The Facies Channel Modeling module of IRAP-RMS^{TM} is used to build the reservoir model in this study. This is an "object–based modeling" module that uses the "Marked Point–Boolean Process" stochastic method (RMS 2009). In addition, the Sandbody mode, used for modeling single cut-and-fill channels or for direct modeling of channel-belt geometries of IRAP-RMS^{TM}, was used to develop the channel system. The basic workflow used herein for the static connectivity modeling is illustrated in Figure 2.

In this study, the grid dimensions of the 3D grid model are 7.2 mile x 3.7 mile x 150 ft (11.6 Km x 5.9 Km x 45.7 m). The grid model is made of 97 columns, 191 rows, and 50 layers which generate 926,350 cells. The dimensions of each cell are 200 ft x 200 ft x 3 ft (approximately, 61 m x 61 m x 1 m) in the X, Y, and Z directions.

There were no direct measurements available regarding the channel depth, channel width and channel amplitude of the streams that deposited the Lower Sterling Formation. Rather, this information had to be inferred from limited outcrop data, net pay of producing gas field, channel classification, analogue data and correlation for alluvial channels. The method used to estimate the channel dimension is described in the following section.

Channel Dimension

Based on Alaska Oil and Gas Conservation Commission (AOGCC) 2005 data, net-to-gross ratio of the Sterling formation in Sterling Field could be approximately 21% to 43%. Due to scarcity of channel volume fraction data, seventeen channel facies volume fractions (CFV) ranging from 10% to 90%, with an equal increment of 5% were considered for this study.

The classification of alluvial river channels according to the type of sediment load as proposed by Schumm, 1968 and based on Flores and Stricker (1993); Flores et al. (1997) work, three channel sinuosities, typical of low sinuosity bed load streams, 1.1, 1.2, and 1.3 were considered for this study.

The work by Hayes et al. (1976) concluded that the Lower Sterling was deposited by meandering streams that flowed south to south east, parallel to the basin axis. Therefore the paleoflow direction was assumed NW-SE for the purpose of the facies channel modeling (FCM).

Based on AOGCC (2005) report, the net pay sand thickness of the Sterling Formation in different eastern Cook Inlet fields are 20 ft, 25 ft, 53 ft, 60 ft, and 88 ft (approximately, 6.1 m, 7.6 m, 16.2 m, 18.3 m and 26.8 m). Also the channel sand thickness from the South Clam Gulch outcrop representing the Lower Sterling Formation varies from 15 ft to 35 ft (4.6 – 10.7 m approximately) (Flores et al., 1997). Finally, seven sand body thicknesses (15ft, 20ft, 25ft, 35ft, 53ft, 60ft and 88ft) were considered herein to calculate channel depth for FCM.

The sandbody thickness was decompacted by 10% before calculating original channel depth (Lorenz et al., 1985) in order to convert sandstone to sand. Consequently, these channel depths are prerequisite for the calculation of true paleo channel widths. For each sandbody thickness, channel depth was calculated based on the work of Dalrymple (1998) who proposed the following equation to calculate channel depth from sandbody thickness for a low sinuosity river.

Channel Depth (m) = 0.7692* Sand Thickness (m) - 0.4945 ………………………. (1)

In a study by Mackin (1956), it was concluded that as channel sinuosity decreases from tortuous to straight, the width to depth ratio of the channel increases. As the lower Sterling formation was deposited by low sinuosity bed load streams, the highest channel width-to-depth (W/D) ratio for a channel of sinuosity 1.1 and the lowest channel W/D ratio for a channel of sinuosity 1.3 may be expected.

Schumm (1963) analyzed morphologic and sediment characteristics of stable alluvial rivers from the Great Plain area and derived a correlation between the channel sinuosity P (ratio of channel length to valley length) and the channel width-to-depth ratio F as,

$P = 3.5 F^{-0.27}$ ………………………………………………………………… (2)

In this study, equation 2 was used to calculate the channel width for each sinuosity (1.1, 1.2, and 1.3) and the channel depth. These channel widths were used to calculate the channel amplitude as described below. The channel W/D ratios as calculated herein are 73, 53 and 39 for sinuosity 1.1, 1.2 and 1.3, respectively.

The empirical data of Leopold and Wolman (1960) was used to develop an equation for the channel amplitude that was used for our study to relate low sinuosity (1.12 to 1.26) meandering channel amplitude with channel width. The equation is as follows,

Channel Amplitude (ft) = 5.2581 * Channel Width (ft) - 861.07 ……………… (3)

Model Description

In this study, three different channel data sets for sinuosity 1.1, 1.2 and 1.3 were considered. Each data set was modeled using 17 channel volume fractions ranges from 10% to 90% with an equal increment of 5% resulting in 51 model scenarios. Due to uncertainty in the input data each scenario was run 10 times which resulted in 10 realizations in each scenario and totaling 510 scenario models. The summary statistics of the channel data set is shown in Table 1, which is used as a basic input to object based FCM. Ten wells of P series (P1 to P10) and five wells of the M-series (M1 to M5) placed in different part of the 3D model (Figure 3) were considered for this study.

Static Connectivity & Effective Static Connectivity

Static connectivity was calculated for 15 individual wells (P & M series) in each of the 510 models. The "Geometric Connectivity" module of IRAP-RMS™ was used to calculate the static connectivity for each individual well. This module calculates the volumes of the cells connected to a well or group of wells in the model.

Since one well may not drain the entire reservoir, a new term called ***"Effective Static Connectivity (ESC)"*** was coined that represented the static connectivity of a single well with any possible drainage area. The ESC of a single well calculated herein represents static connectivity of a single well for 50 acre drainage area (an ellipsoid of X=681.5 ft, Y=764.9 ft and Z=150 ft). The outcome of static connectivity analysis is summarized in the results and discussion section.

RESULTS AND DISCUSSION

The model outcomes were analyzed for

- PS, which is defined as the percentage of wells intersecting channel facies in any particular realization;
- SC, which is defined as the summation of static connected volume percentage of all the wells in a realization divided by the number of wells intercepting the channel facies in that particular realization; and
- ESC, which is defined as the summation of effective static connected volume percentage of all the wells in a realization divided by the number of wells intercepting the channel facies in that particular realization.

Probability of Success (PS %)

Analysis of PS is presented in Figure 4. It is evident from the figure that the coefficient of variation (CV) of PS decreases with increase of CFV%. It is also evident that below 40% of CFV, the mean PS is high for sinuosities of 1.2 and 1.3 at CFV's of 10%, 15%, and 25% (Figure 5). It may be possible that this phenomenon is due to moderate channel width-to-depth ratios (53:1) and moderate sinuosity in channels with a sinuosity of 1.2. Also the high sinuosity values and low width-to-depth ratio (39:1) for channels with a sinuosity of 1.3 help in the vertical stacking and lateral spreading of channel systems covering large model areas and giving rise to the high PS at lower CFV%. This interpretation is also supported by Figure 6 which show the average 2D surfaces representing P50 for CFV of 10% and different sinuosities, respectively.

Above 25% of CFV, a sinuosity of 1.1 gives the highest PS at 30%, 35%, and 40% of CFV. It may be possible that, above 25% of CFV, the availability of sufficient channel volume and the high width-to-depth ratio (73:1) of channels with a sinuosity of 1.1 connect the channel system that covers a significant model area and gives high PS. This interpretation is also supported by Figure 7 which show the average 2D surfaces representing P50 for CFV of 35% and different sinuosities, respectively.

The analysis of PS also shows that between 20% and 40% of CFV, the mean PS gives a value ranging approximately between 62% and 90%, considering all the sinuosities. It was also evident that above 70%–75% of CFV, the mean PS becomes 100% for all sinuosities.

Static Connectivity Percentage (SC %)

The analysis of SC% shows (Figure 8) that above 30% of CFV, the mean SC is greater than 90% for all sinuosities. In the range of 20% to 30% of CFV, the mean SC% is approximately 64% to 91% considering all sinuosities. The threshold channel facies volume for which the mean SC becomes 100% is 65% for all sinuosities. Below 40% of CFV, the mean SC% is higher for sinuosities of 1.1 and 1.3. These observations may be typical for static connectivity in low sinuosity gas reservoirs

Effective Static Connectivity Percentage (ESC %)

The general trends in Figure 9 suggests that mean ESC% decreases with increase in CFV%. It is also evident that above 40% of CFV, the mean ESC for sinuosities of 1.1, 1.2, and 1.3 ranges from 0.21%-0.24%, 0.21%-0.23%, 0.21%-0.22%, respectively. Below 40% of CFV, the mean ESC% for sinuosities 1.1, 1.2, and 1.3 ranges from 0.26%-0.54%, 0.24%-0.49%, and 0.22%-0.62%, respectively. It was also observed that below 40% of CFV, the ESC% is high for a sinuosity of 1.1 in most of the scenarios. The possible reason for this could be the higher channel width-to-depth ratio (73:1) for channel deposits with a sinuosity of 1.1. This results in high channel width encountered by any well in a particular location.

Assuming homogeneous porosity and permeability in our channel facies, higher effective static connectivity in channel deposit of sinuosity 1.1 signifies that good well productivity can be expected in channel deposit of sinuosity 1.1 as compared to sinuosities of 1.2 and 1.3.

Conclusion

The major conclusions that may be derived from this work are as follows.

- The probability of success depends on the degree of vertical stacking and lateral spreading of the channel system in the model area. At lower channel facies volume (approximately 10% to 25%), the probability of success is high for sinuosities of 1.2 and 1.3. Moreover, approximately above 40%-45% of channel facies volume, the probabilities of success is greater than 90% for all sinuosities.

- Above approximately 30% of channel facies volume, the mean static connectivity is greater than 90% for all sinuosities.

- Above approximately 65% of channel facies volume, the role of channel dimension is negligible and mean static connectivity is 100%.

- Effective static connectivity for 50 acre well spacing is controlled by channel width-to-depth ratio in most scenarios. At lower channel facies volume, the effective static connectivity is higher for sinuosity 1.1 in most of the cases.

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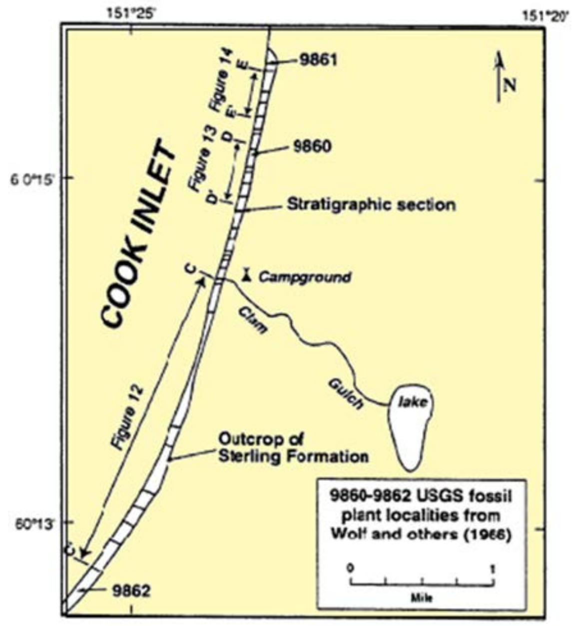

Figure 1: Map of Sterling formation outcrops in the Clam Gulch area (Courtesy of Flores et al., 1997)

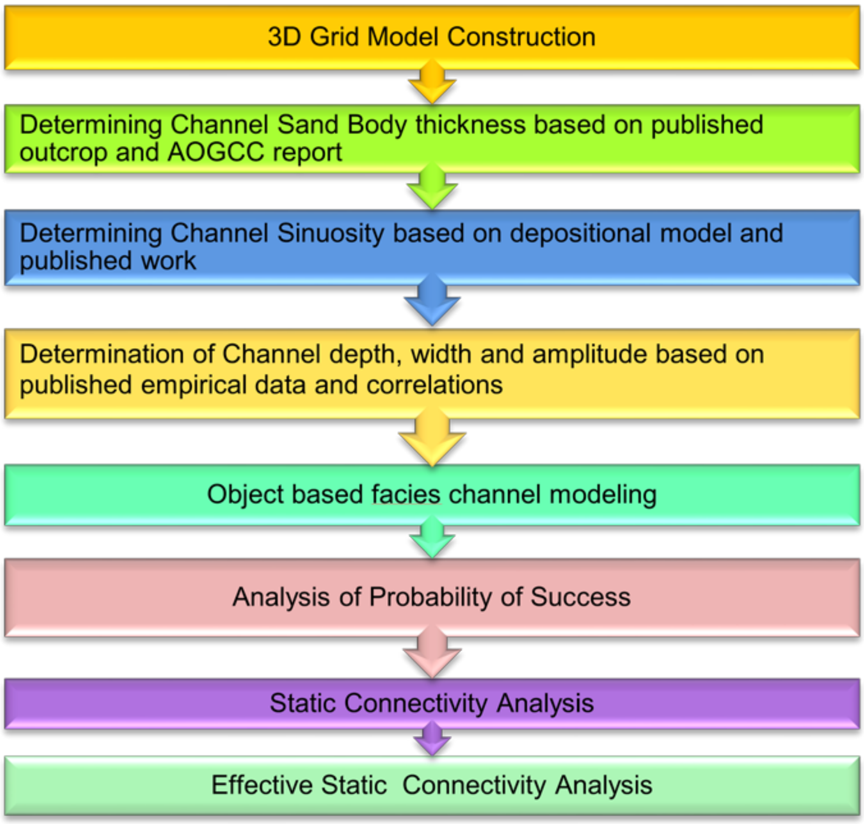

Figure 2: Work Flow of Static Connectivity Modeling

Table 1 : Summary Statistics of Channel Dimension for Different Sinuosities

Channel Depth (ft) Statistics			
Mean	34.16	Minimum	11.07
Standard Deviation	22.15	Maximum	72.84
Channel Width (ft) Statistics			
	Sinuosity=1.1	Sinuosity=1.2	Sinuosity=1.3
Mean	2484	1800	1338
Standard Deviation	1611	1167	868
Minimum	805	583	434
Maximum	5298	3838	2854
Channel Amplitude (ft) Statistics			
	Sinuosity=1.1	Sinuosity=1.2	Sinuosity=1.3
Mean	12202	8604	6175
Standard Deviation	8471	6137	4563
Minimum	3373	2206	1419
Maximum	26996	19322	14144

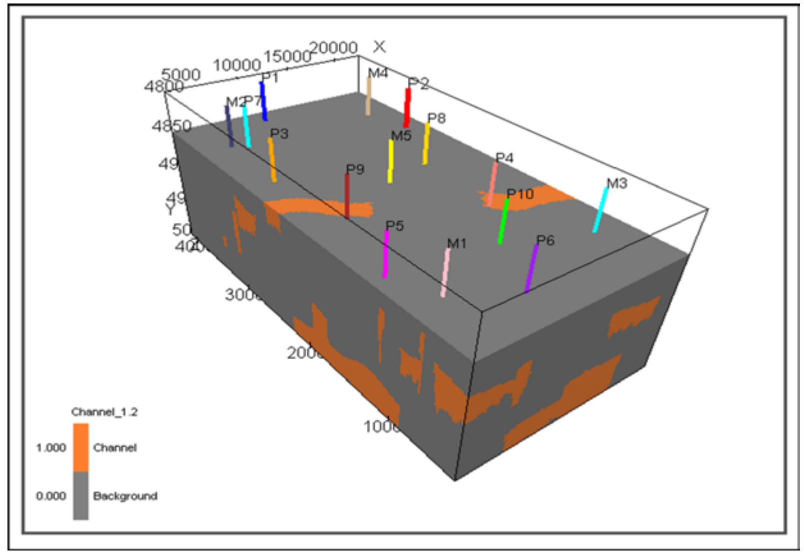

Figure 3: 3D Static facies channel model for a sinuosity of 1.2 and a channel volume of 20% (Realization No. 10). Note that the orange color represents the reservoir volume occupied by the channel facies and grey color represents the background facies in the reservoir model. The XY coordinates are in feet. Model contains 15 wells of P and M series. Here well nomenclature is arbitrary.

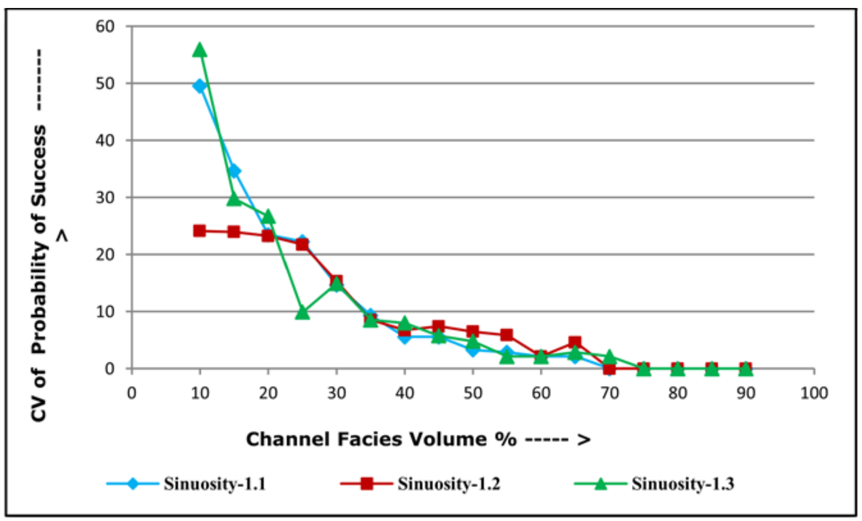

Figure 4: Coefficient of variation of Probability of success vs. CFV% for all sinuosities. Note that at lower channel volume, CV of probability of success is lower for sinuosity 1.2 in comparison to sinuosity 1.1 and 1.3

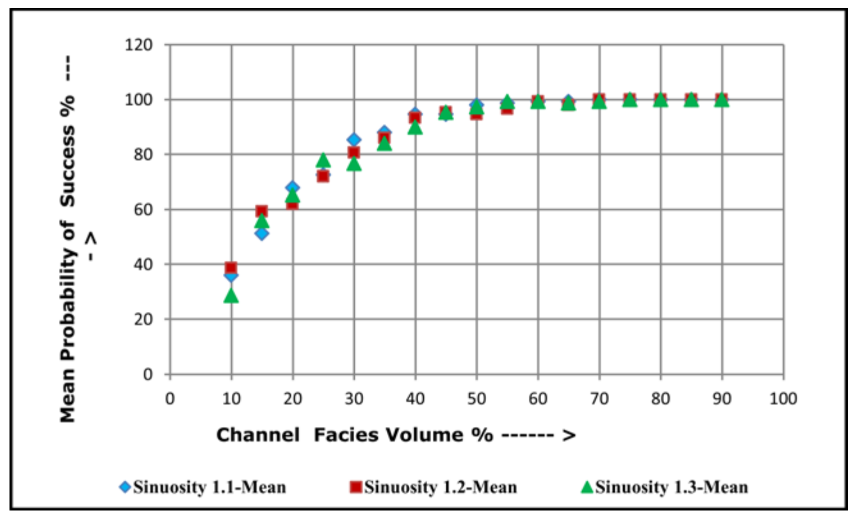

Figure 5: Scatter plot showing mean Probability of success vs. CFV% for all sinuosities. Here at lower channel volume, the mean probability of success is higher for sinuosity 1.2 and 1.3 than 1.1.

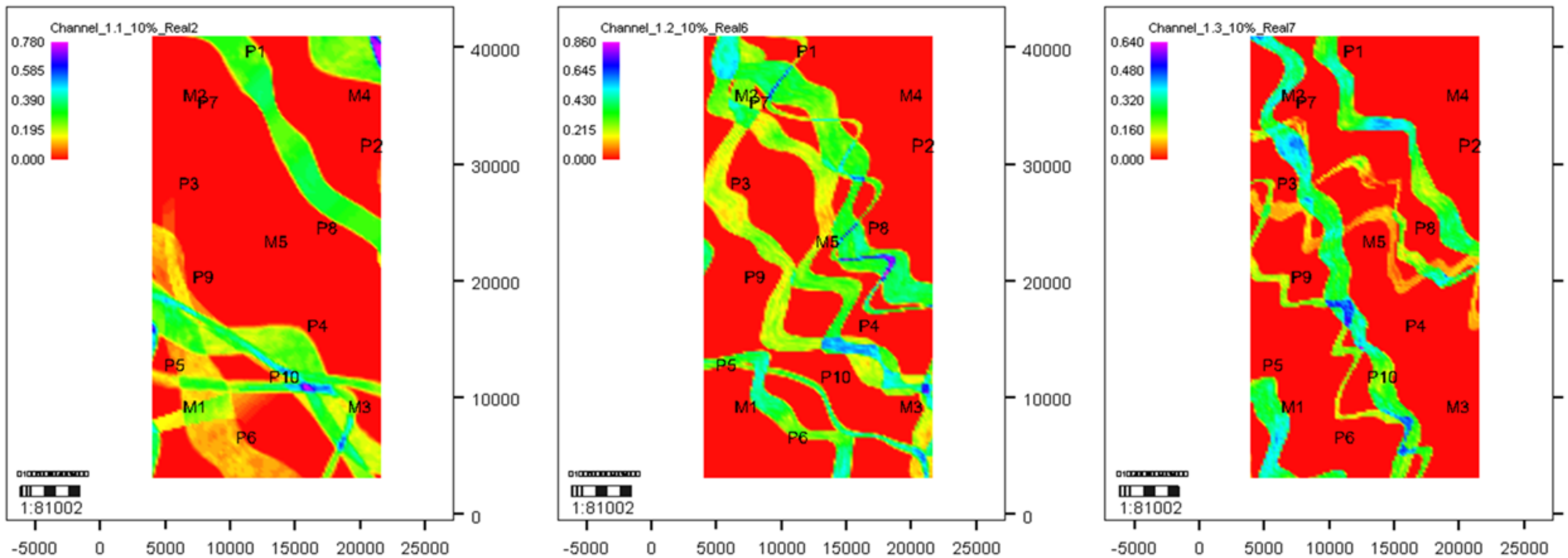

Figure 6: Average 2D surfaces representing P50 for a CFV of 10% and sinuosities of 1.1, 1.2, and 1.3. The XY coordinates are in feet.

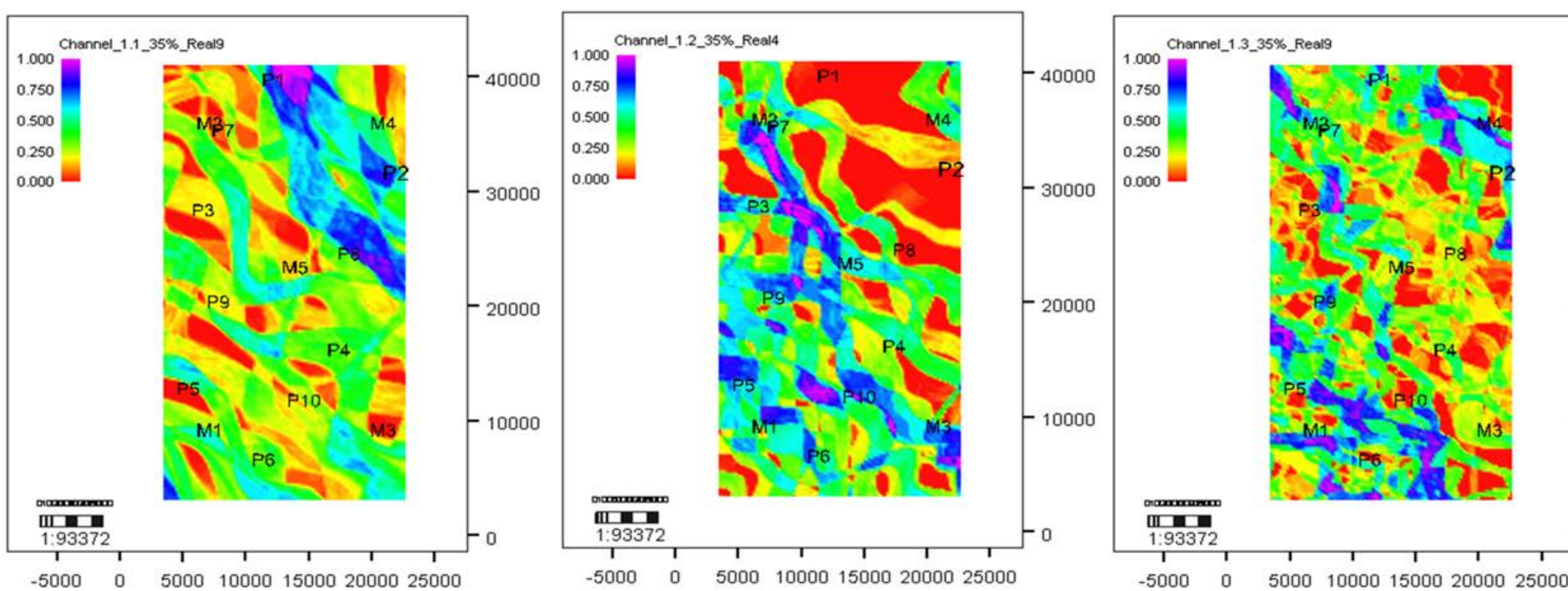

Figure 7: Average 2D surfaces representing P50 for a CFV of 35% and sinuosities of 1.1, 1.2, and 1.3. The XY coordinates are in feet.

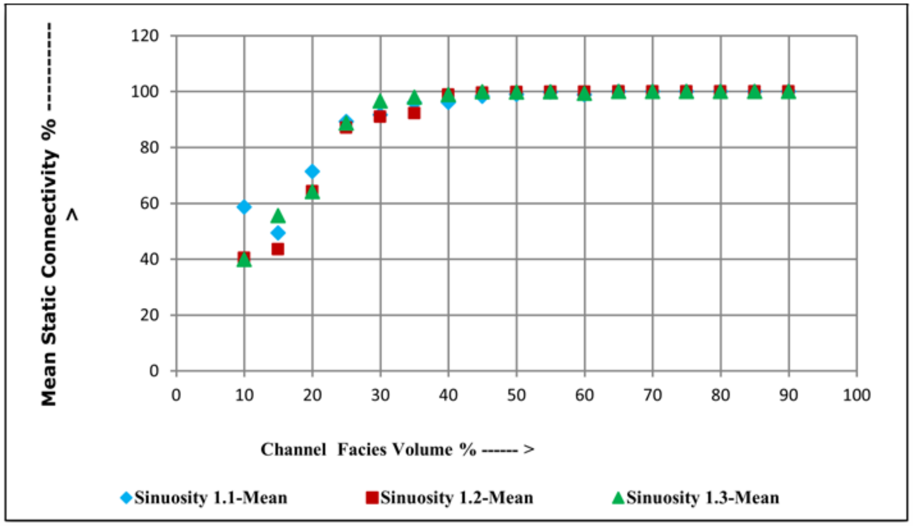

Figure 8: Scatter plot showing mean SC% vs. CFV% for all sinuosities

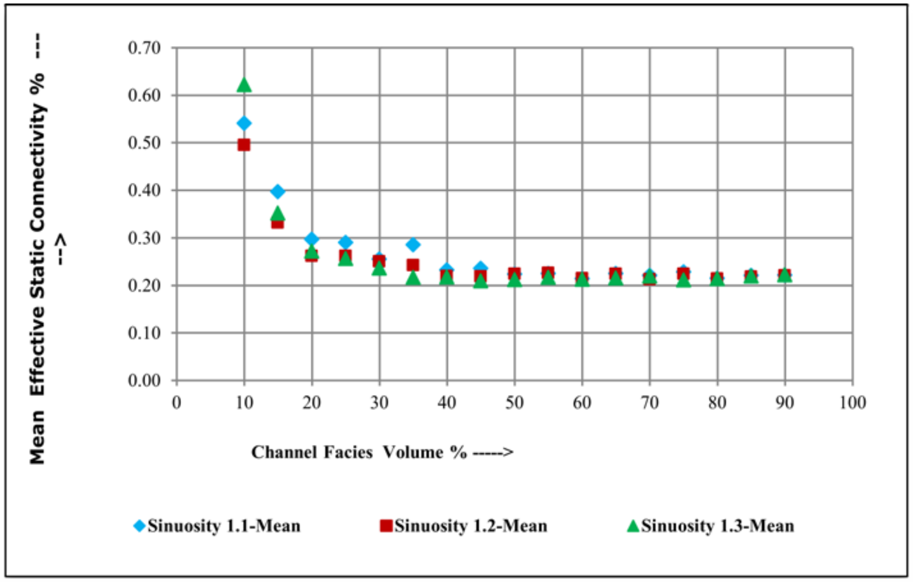

Figure 9: Scatter plot showing mean ESC% vs. CFV% for all sinuosities