Integration of geology, seismic, and geochemical data — Theory and practice in Cheeseburger Field, Stonewall County, Texas, USA

Gary K. Rice[1], Greg King[2], and Jay Henson[3]

Abstract

Difficult-to-find petroleum resources and expensive drilling drive the need for improved exploration methods. Although improvement can be made by technically advancing individual methods, greater improvement comes from integrating existing independent exploration methods to dramatically improve drilling success. Exploration integration is often discussed, but it is less often carried out. A reason exploration integration has been limited may be due to the lack of clearly defined integration methods. In this study, we looked at the integration of independent exploration methods; we studied its fundamental principles, how it works, and why it is effective. Derived from basic probability theory, a simple map overlay of independent exploration data can be an effective integration method. Probability calculations determine the probability of a successful well from known probabilities of integrated independent techniques. A successful integration of data from Cheeseburger Field, Eastern Shelf of the Midland Basin, Stonewall County, Texas, illustrates how integration of 3D seismic, subsurface geologic, and surface geochemical data improve drilling results beyond those achieved from any single method used alone. In Cheeseburger Field, 3D seismic and subsurface geology resulted in $4/7 = 57\%$ successful wells. After integrating geochemical exploration data, results improved to $4/5 = 80\%$. Modern petroleum exploration is a multitool, integrated information science. Probability theory provides a means for predicting outcome of integrating independent exploration methods. Enhanced exploration success can be achieved by combining independent and complementary exploration methods in this integration process.

Introduction

Petroleum exploration history documents numerous geophysical, geochemical, and geologic methods for finding oil and gas. Exploration methods are traditionally used singularly or sparingly (even reluctantly) combined with other methods.

One-method-at-a-time exploration essentially confined exploration to areas where methods of choice worked. Additional areas for exploration opened up as "tried-and-true" methods were improved and refined to solve specific problems.

Integration reluctance stems from three inherent problems with the integration process:

1) As we shall see, the best methods to integrate are independent techniques. Using an independent technique often requires working outside our chosen discipline in which we experience the uncertainty of working outside our comfort zone.
2) The integration process can be problematic. How do we put together disparate techniques with different kinds of data and different spatial resolutions?
3) Adding more exploration methods increases cost. Do the benefits justify additional expenditures?

These are the basic problems with exploration data integration and a brief explanation of why integration is not more frequently carried out. We will address the first problem only by suggesting that the goal of petroleum exploration is to find oil or gas and not to find oil or gas using exploration method X, or Y, or Z. Explorationists should embrace a multidisciplinary approach whether it is by a few well-rounded individuals or by a team of less versatile experts. The second problem, how to carry out the integration process, is addressed here in detail. We will find that by integrating interpreted data, the integration process can stand on its own with minimal input from integration phobic specialists. The third problem, cost versus benefit, is a business decision. The process described here provides a way to calculate benefits resulting from integration.

Cheeseburger Field was discovered using 3D seismic data. Subsurface geology data were limited, but there was a good geologic understanding of the area.

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[1] GeoFrontiers Corporation, Dallas, Texas, USA. E-mail: aapg3@geofrontiers.com.
[2] Salida Exploration, Abilene, Texas, USA. E-mail: greg.salida@gmail.com.
[3] Henson Exploration L.P., Abilene, Texas, USA.

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Near-surface geochemical exploration (soil gas hydrocarbon) data were collected during field development. The problem was how to integrate these very different data sets.

Definitions

The use and meaning of three terms used throughout this paper are very important and are given here for clarity:

1) Integration is to unite with something else, to incorporate into a larger unit or blend into a functioning or unified whole (Merriam-Webster's Online Dictionary, 2009). Hence, we are using integration to mean putting multiple exploration methods together resulting in a new combined interpretation.
2) Independent means not dependent on the other methods and not influenced by previous outcomes. For example, the outcome of two wells is independent if the result of the second well does not depend on what happened with the first well. Exploration methods are independent if they depend on different measurement mechanisms. For example, subsurface geology and seismic measure structure, but by using very different measurements.
3) Complementary means supplying additional information that the other methods lack. For example, seismic supplies structural information, whereas geochemical exploration supplies information about petroleum. Therefore, seismic and geochemical exploration are clearly complementary techniques.

Background

Since the dawn of petroleum exploration, research efforts have been focused on understanding and developing complex technologies, such as seismic (Chopra and Marfurt, 2005), geology (Howell, 1930), and geochemical exploration (Davidson, 2004). Throughout the less than 100-year history of modern petroleum exploration, relatively limited efforts and resources have been dedicated to integration.

Cases exist in which seismic and geochemical exploration data were successfully integrated. Rice (1989) describes two cases of geochemical exploration and 2D seismic integration using simple data overlays. One integration case in LaSalle County, Texas, USA, resulted in one discovery and one offset well. The other case in the Michigan Basin, USA, resulted in a new field discovery. Combined results were 100% (3/3) resulting in two new fields, but more importantly, these cases demonstrated the power and importance of combining independent and complementary techniques. Hitzman et al. (2002) integrate microbial data with 3D seismic to successfully identify a reservoir in a structural trough in Montague County, Texas, USA. Drilling results were 90% (9/10) within the positive integration areas. Jones and LeBlanc (2004) compare Morrow (southwest Kansas, USA) exploration methods and demonstrate improvement from 41% (9/22) to 90% (9/10) drilling success when soil gas hydrocarbon data were included in the integration. Although this may not be an exhaustive literature review, there have been few cases reported of drilling on integrated geologic, seismic, and geochemical data.

Belt and Rice (1996a, 1996b) integrate geochemical shallow core data with bottom cable 3D seismic data and find the two data sets to be complementary using simple overlay procedures to find vertical migration pathways from reservoirs at depth. Table 1 (modified from Schumacher, 2011) is a compilation of literature studies in which conventional and geochemical methods were tested. Drilling results inside and outside positive geochemical areas strongly suggested drilling success could be improved by integrating geochemical data with geology and seismic data.

How can putting together sets of methods with stand-alone probabilities of success 50% and below achieve success rates of 70%–80%? Such tremendous success improvement could be easily dismissed except for the significant number of cases, different authors, and even different methods reported. All the studies in Table 1 reported similar drilling results. How is this possible?

Our search for integration methods included pattern recognition methods that have been successful in many kinds of data integration and reduction, including exploration. Discriminant analysis, cluster analysis, and principal component analysis are methods widely used in exploration, including geochemical exploration. More advanced techniques, including neural networks and Bayesian analysis, may play roles in deriving meaning from very complex data sets. All of these methods are effective, have limitations, and require computational effort. However, in this study, we were seeking to determine the fundamentals of exploration integration in its simplest and most basic form.

The earliest integration with mathematical support can be traced to Pirson (1941a, 1941b) whose probability theory is used to calculate results from integrating independent exploration methods and calculating drilling risk. Saunders et al. (2002) describe using probability to support integrating five different exploration techniques.

In this study, we investigated elementary probability theory, its application in modern exploration integration, and if there was a mathematical way to back up potential integration success in Table 1. We also used probability theory to constrain and guide the integration process.

Probability theory

Probability theory permeates society and the human experience. Probability calculations drive risk analysis in insurance, banking, and disease control. Probability is important to exploration investment as companies and individuals seek to understand risk-adjusted returns on investments (Rose, 2001). Probability is inherent in the exploration process, but often is not explicitly declared.

The theory of probability is based on random chance. Although randomness is the antithesis of a highly controlled exploration environment, it is the random part of exploration uncertainty that we seek to understand. Probability can quantify the random part of exploration that we cannot control.

Probability concepts can be illustrated using a random coin toss. With only two choices, either heads or tails, a coin toss is the simplest random chance problem. A fair coin toss has a 50% chance of resulting in a head and a 50% chance of resulting in a tail.

Our discussion requires dealing with only two simple equations that were adapted from Gnedenko and Khinchin (1961) and can be found in most elementary probability books. The first equation states the probability of all possible outcomes add to 100%, which can be expressed as

$$PE_1 + PE_2 + \cdots + PE_n = 1 = 100\%, \tag{1}$$

where PE_1 is the probability of event 1, PE_2 is the probability of event 2, etc. In the case of a coin flip, the probability of a head is PH and the probability of a tail is PT. The sum of PH and PT add to 100% because those are the only choices. There is a 100% chance the coin was flipped and landed either head or tail. If we flip a single coin many times, we expect PH to be approximately 50% and PT to be approximately 50%. The total of PH and PT is exactly 100% because only those two events are allowed.

A second probability equation states that the probability of all n independent events occurring is the product of each single event occurring, which can be written as

$$P(\mathrm{E}_1 \text{ and } \mathrm{E}_2 \text{ and } \ldots \text{and } \mathrm{E}_n) = PE_1 \times PE_2 \times \cdots \times PE_n. \tag{2}$$

Using our coin flip example, equation 2 states that the probability of flipping two heads in succession is the product of the probability of flipping a head on the first flip 50% times the probability of flipping a head on the second flip 50%, which is $50\% \times 50\% = 25\%$. Hence, the probability of flipping two heads in a succession is 25%.

Equations 1 and 2 are simple, but how can they help finding petroleum? Let us put them into petroleum finding terms. If PW is the probability of making a well, and PD is the probability of a dry hole, then by equation 1, we get

$$PW + PD = 100\%. \tag{3}$$

Examining equation 3 and using the same logic developed for equation 1, if we have either a well or a dry hole, and with no other possible outcome, then the sum of those two probabilities is 100%. Therefore, if we know the probability of a well, we can subtract that probability from 100% and calculate the probability of a dry hole, and vice versa.

Equation 2 expresses the probability of all n independent events occurring, but in exploration, we are more interested in one of n events occurring. For example,

Table 1. Compilation of exploration methods with drilling results from Schumacher (2011). See Schumacher (2011) for explanation.

Method	Geology + geophysics only	Wells within seepage anomaly	Wells outside seepage anomaly	References
Iodine	32/89 discoveries	27/31 discoveries	5/58 discoveries	Leaver and Thomasson (2002)
	36%	87%	9%	
Radiometric	104/184 discoveries	80/99 discoveries	24/85 discoveries	Weart and Heimberg (1981) and Curry (1984)
	57%	81%	28%	
Microbial	153/422 discoveries	133/177 discoveries	20/245 discoveries	Meyer et al. (1983) and Beghtel et al. (1987)
				Mello et al. (1996) and Hitzman et al. (2002)
	36%	75%	8%	Wagner et al. (2002) and Schumacher (2007)
Soil gas	18/52 discoveries	10/14 discoveries	8/38 discoveries	Wyman (2002)
	35%	71%	21%	
Soil gas (Petrex)	75/141 discoveries	74/98 discoveries	1/43 discoveries	Potter et al. (1996)
	53%	76%	2%	
Micromagnetics	621/1579 discoveries	531/658 discoveries	90/921 discoveries	Foote (1996) and Schumacher and Foote (2006)
	39%	81%	10%	

what is the probability of making at least one well if we drill six holes? We cannot use equation 2 directly because that equation applies only to all of n events happening. We can get what we want by combining equations 1 and 2. If we make at least one well in n tries, then we did not drill all dry holes. We can calculate the probability of all dry holes using equation 2, which is expressed in equation 4 as

$$PD_{\mathrm{all}} = PD_1 \times PD_2 \times \cdots \times PD_n. \tag{4}$$

Then, to find out the probability of at least one well being not dry, we use equation 1

$$PW_{(\text{at least one})} = 100\% - PD_{\mathrm{all}}. \tag{5}$$

Equation 5 subtracts the probability of all wells being dry from 100% to get the probability that at least one well produces. That leads us to equation 6 in which we calculate the probability of making a well using the individual probabilities of success from drilling each of n wells. The probability of each well is independent. That is, the outcome of each well does not depend on the outcome of any other well.

$$PW_{(\text{at least one})} = 100\% - (100\% - PW_1) \times (100\% - PW_2) \ldots (100\% - PW_n). \tag{6}$$

Equation 6 simply says the probability of drilling at least one well is the product of drilling a dry hole each time multiplied together and then subtracted from 100%.

However, in exploration integration, we are interested in the probability of making a well based on more than one type of exploration data. This can be done by considering the above probability equations a little differently.

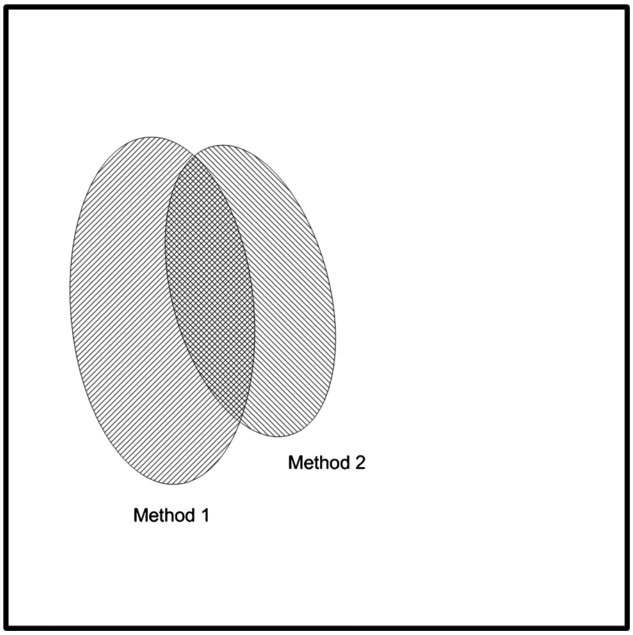


Figure 1. Interpreted methods 1 and 2 overlap.

If the probability of making a well using method 1 (PM_1) is 30% and the probability of making a well using method 2 (PM_2) is 20% in a particular area, what is the probability of making a well by combining (integrating) independent methods 1 and 2? How should methods 1 and 2 be integrated?

The example in Figure 1 illustrates the interpreted result of methods 1 (up to the right diagonal lines) and 2 (down to the right diagonal lines). The two diagonal line patterned areas in Figure 1 are the interpreted results in which each method indicated a petroleum reservoir. As is common, the two different methods yielded somewhat different results and overlap only in part of the area.

Historically, there have been two approaches to this dilemma. One solution has been to drill using only method 1 because it is 30% effective, whereas method 2 is only 20% effective. Although this approach makes some sense, it does not make use of more than one method and therefore does not involve integration.

Another solution has been to drill where the two methods overlap. This method usually is done by overlaying interpreted maps of methods 1 and 2, as shown in the crosshatched area in Figure 1. Overlay is based on the logic that two (or more) methods are better than one, and the best results (highest probability) will be where the methods agree. Criticisms of the overlay approach include the following:

1) It is too simple. Other integration methods are more mathematically elegant.
2) As more methods are added, methods overlap in successively smaller areas, which diminish the size of the drilling target.
3) All methods may not overlap.

Other integration methods have been used, including summing (or averaging) normalized data, drawing lines between the central points of each interpretation, and finding the point nearest line intersects. These, and other creative integration methods, have been used without a good theoretical foundation.

Using the example in Figure 1, drilling within the method 1 area has a 30% chance of making a well and a 70% chance of making a dry hole (from equation 5). Likewise, drilling inside the method 2 area has a 20% chance of making a well and an 80% chance of making a dry hole. So, where to drill?

One solution would be to drill two wells, one well on the area outlined by method 1 and the other on the area outlined by method 2. The probability of both wells being dry is $80\% \times 70\% = 56\%$ according to equation 4. Using equation 5, the probability of at least one of the two wells being productive is $100\% - 56\% = 44\%$. Or using equation 6, $1 - (1 - 0.30)(1 - 0.20) = 0.44 = 44\%$.

But how can we get these odds and drill only one well? Using the same logic and with the assumption that drilling anywhere within the method 1 area has a 30%

chance of success and drilling anywhere within the method 2 area has a 20% chance of success, then with one well we can drill where methods 1 and 2 overlap. We have method 1 giving that location a 30% chance of success and method 2 gives that location a 20% chance of success. If methods 1 and 2 are independent, then drilling where the two methods overlap will give the same success as drilling two wells where the methods do not overlap which was 44%.

In this case, equation 6 was evaluated using the probability of drilling a well using method 1 and the probability of drilling a well using method 2. The probability of drilling a well PW_1 using method 1 is PM_1 and the probability of drilling a well PW_2 using method 2 is PM_2. By substituting these equivalent terms, equation 6 can be rewritten in terms of independent exploration methods as equation 7.

$$PW = 100\% - (100\% - PM_1)(100\% - PM_2)\ldots(100\% - PM_n). \tag{7}$$

Pirson (1941b) applies equation 7 to the integration problem by multiplying the probabilities of the following independent exploration methods:

1) probability of making a producing well using only geologic data
2) probability of making as well using only seismic data
3) probability of making a well using only geochemical data
4) probability of making a well by random drilling.

This method can be effective only to the extent the methods are independent and when the probability of each method is known.

Cheeseburger Field

Located in Stonewall County, Texas, USA, Cheeseburger Field is on the Eastern Shelf of the Midland Basin. Frye (Permian) sandstones often occur in eroded sections of underlying Stockwether limestone (Figure 2). Production from Frye sandstone is approximately 1100 m (3600 ft) below the surface. Although the other sandstones and some limestones are productive in the region, only the Frye sandstone has been productive in the area mapped in this report. The limestone/sandstone interface had sufficient acoustic impedance difference to allow imaging channel cuts in seismic data. A channel-fill isopach, or channel depth, as interpreted from 3D seismic data is shown in Figure 3.

Although channel cuts depicted in Figure 3 appeared as two coalesced channels, subsequent production data suggest that the channels were not connected. Such complex geology would be impossible to map using only subsurface information from a few wells. The seismic data were essential for discovering and developing this oil field. In fact, subsurface geology and seismic data were the only methods used for initial development of Cheeseburger Field.

Figure 3 shows the wells in existence after geology and seismic integration and before the geochemical data were collected. Wells within channel limits (circled) totaled four producers and three dry holes. Four out of seven is 57%, which was good success considering the channel complexity and the fact that the channel-fill included oil productive sandstone, nonproductive shale, and nonproductive water-filled sandstone. These different channel fills were not distinctively different in the seismic data. Therefore, geochemical data were used in an attempt to find oil-bearing parts of the channel.

Interstitial soil gas data were collected using a 3 m (10 ft) auger disaggregation technique. Samples were collected at approximately 150 m (500 ft) grid intervals at locations shown in Figure 4. This sample spacing provided about three samples across the narrowest portions of the seismic-imaged channel. Oil reservoirs were even narrower than the channel width, so only two samples occurred across the narrowest portions of reservoirs. This was much fewer than four samples per target width recommended by Matthews (1996). Approximately 60% of samples were below the background threshold of 2.5 ppm ethane. Overall, the geochemical sample design was minimal for defining what was later determined to be very narrow oil reservoirs.

Geochemical data were processed using methods previously described by Rice et al. (2002). Figure 4 is a map of ethane concentration data. Data were also collected for methane, ethane, propane, *i*-butane, and *n*-butane, but they were not included in Figure 4. All these other petroleum hydrocarbons were highly corre-

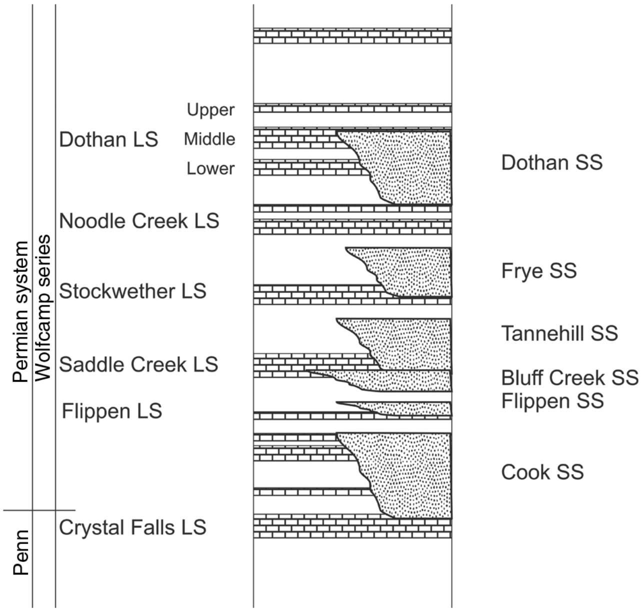


Figure 2. Stratigraphic section of Lower Permian interval, Eastern Shelf, Midland Basin. Modified from Bloomer (1977).

lated ($r > 0.9$), and therefore each hydrocarbon would map similar to ethane. All geochemical data inside the colored portions of Figure 4 indicated above-background petroleum hydrocarbons. Single-sample high concentrations probably were due to higher permeability pathways to the surface, e.g., fractures. These high magnitudes were not important in this study because we were interested only in areas where samples were above the background threshold and areas where samples were below the background threshold.

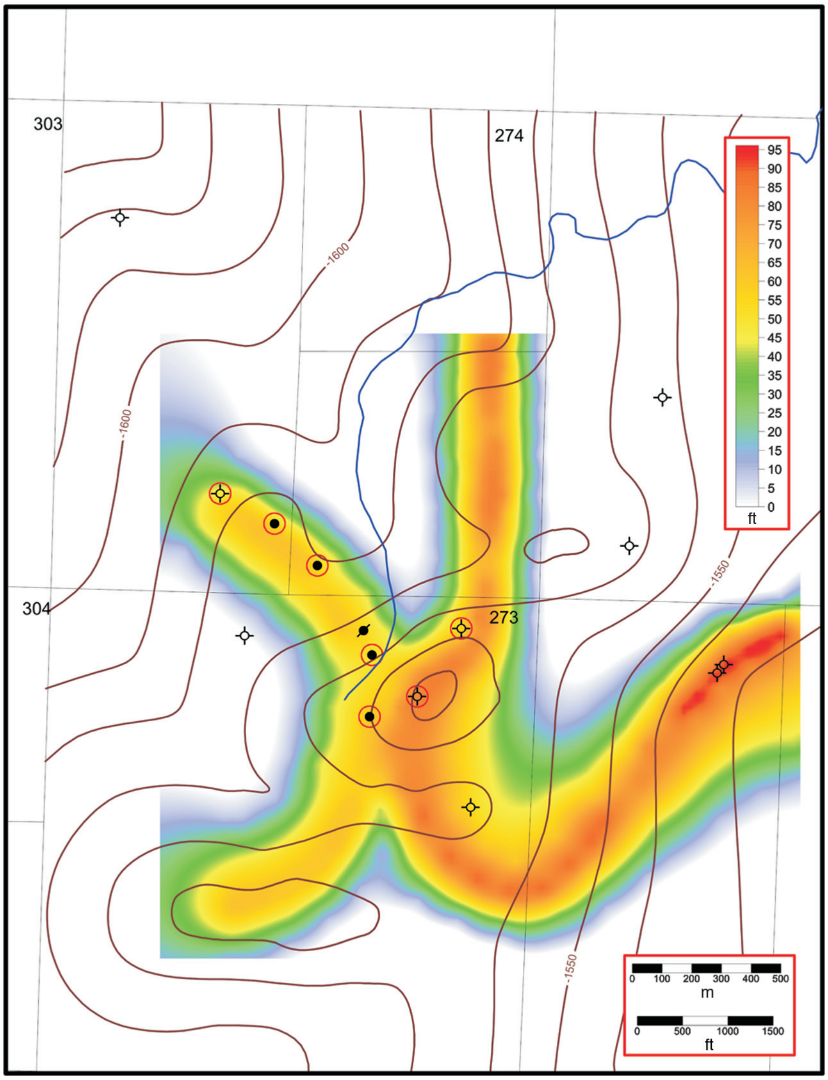
Geochemical data in Figure 4 show areas with above-background concentrations, but not in a pattern that emulated channel boundaries mapped from seismic data depicted in Figure 3. So, the question arose: How do we integrate the geochemical and seismic data? We get a clue from Figure 1 in which we determined overlap of two independent exploration methods should have an improved chance of success. Applying that theoretical concept to our real-world data proved to be rather easy. Because the seismic data were more spatially precise, we used the seismic data to spatially constrain the geochemical data. The concept was to use the channel limits to cut away geochemical data outside the channels. Results are shown in Figure 5.

Figure 5 shows areas within channel limits where petroleum hydrocarbon concentrations were above the background threshold of 2.5 ppm. Areas below background are colored gray. Therefore, Figure 5 shows channel limits, but colored portions of the display show portions of the channel thought to contain oil.

Results

Results in Figure 6 show postintegration wells in square outlines. Postintegration results were four wells and one dry hole for an integrated data success rate of 80%. But how did the drilling results compare with the probability theory? We determined that the success rate of the original geology and seismic integration was 57%. We can estimate the stand-alone geochemical data success rate at approximately 50% based on the authors' experience in the area which is at the low end of

Figure 3. Channel isopach from integrated well and seismic data. Pregeochem wells are circled. Other wells (not circled), including the abandoned discovery well, were drilled prior to this study and were not used in drilling success calculations. Color bar is channel thickness in feet. Brown contours are base of Noodle Creek Ls in feet MSL.



stand-alone probabilities calculated in Table 2 below. Using equation 7, we get

$$
\begin{aligned}
PW &= 100\% - (100\% - 57\%)(100\% - 50\%)\\
&= 1 - (1 - 0.57)(1 - 0.50)\\
&= 0.79\\
&= 79\%. \qquad (8)
\end{aligned}
$$

This result is nearly the same as the 80% actual result obtained at Cheeseburger Field. Of course, such calculated probabilities can be no more precise than the stand-alone probabilities used for the calculations. Cheeseburger Field presented the problem that prompted studying how to integrate geology, seismic, and geochemical data. Although Cheeseburger Field was only a single case and contained too few wells to prove the probability model, it demonstrated a successful application of probability theory to real-world exploration.

Other cases

Additional cases are needed to determine the application of probability in exploration. Some of these cases are listed in Table 1, and not all cases in Table 1 involved data integration as developed in this paper. Most wells were located using conventional integrated geology and seismic data. The result of drilling on geology and seismic and examining drilling results in above-background geochemical areas had the effect of simulating integration, even in cases in which data analysis was done after drilling. We can rearrange equation 7 to calculate the last column in Table 2, which shows the stand-alone probabilities that geochemical methods would have before integration with "geology + geophysics only" data to give the "wells within seepage anomaly" results. For example, stand-alone soil gas probability was calculated using probability of a well

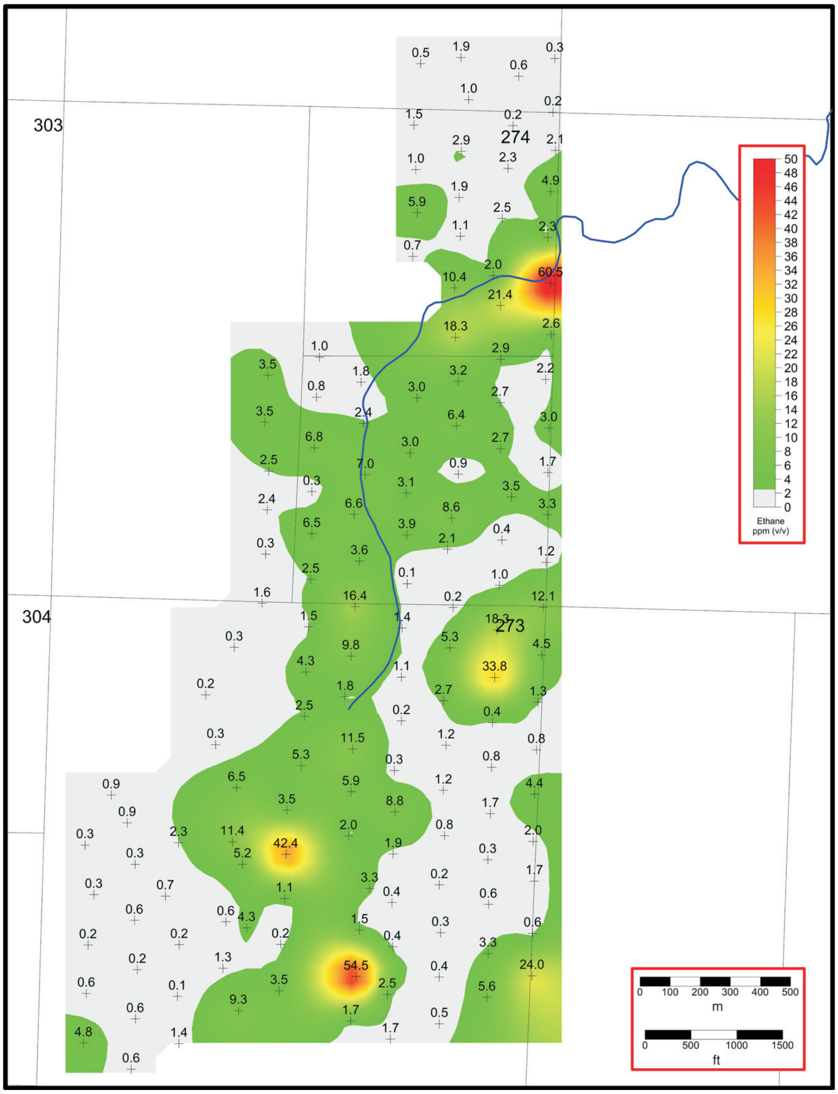


Figure 4. Near-surface ethane concentration distribution.

Figure 5. Integrated seismic and geochemical data.

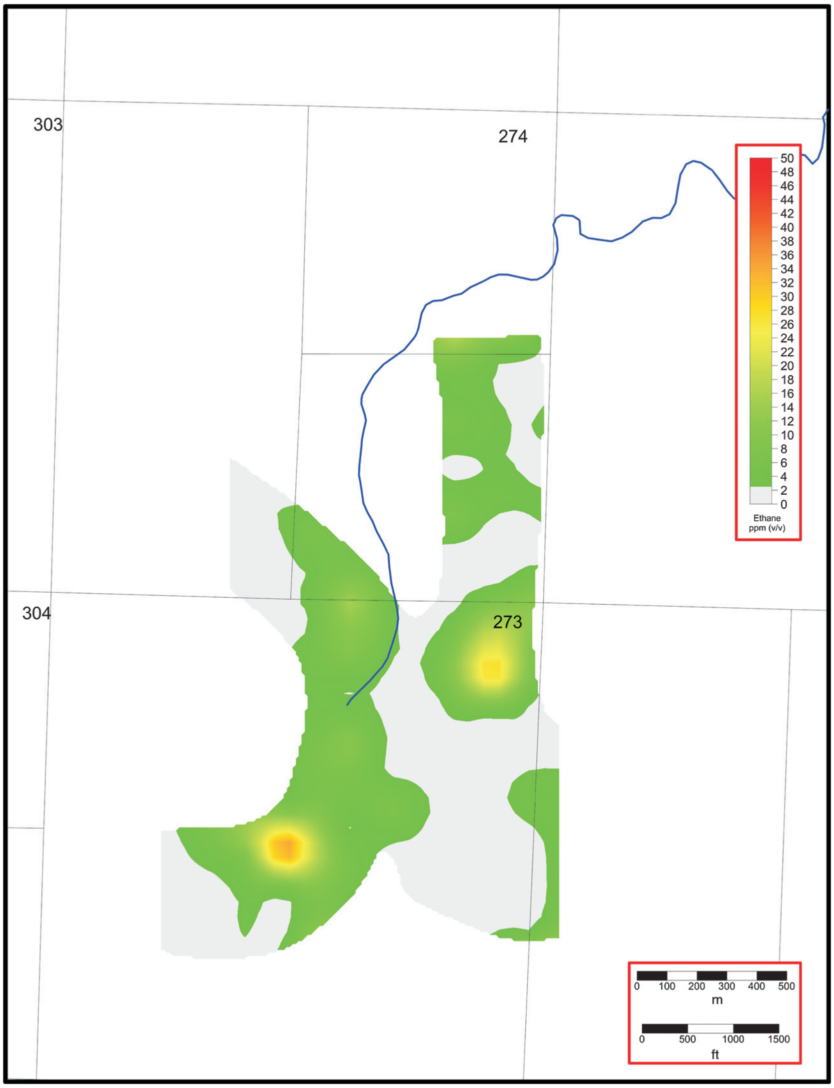


Table 2. Data from Schumacher (2011) with calculated geochemical data probability calculated from equation 7.

Method	Geology + geophysics only	Wells within seepage anomaly	Wells outside seepage anomaly	Calculated geochemical data probability
Iodine	32/89 discoveries	27/31 discoveries	5/58 discoveries	
	36%	87%	9%	80%
Radiometric	104/184 discoveries	80/99 discoveries	24/85 discoveries	
Microbial	153/422 discoveries	133/177 discoveries	20/245 discoveries	
	36%	75%	8%	61%
Soil gas	18/52 discoveries	10/14 discoveries	8/38 discoveries	
	35%	71%	21%	55%
Soil gas (Petrex)	75/141 discoveries	74/98 discoveries	1/43 discoveries	
	53%	76%	2%	49%
Micromagnetics	621/1579 discoveries	531/658 discoveries	90/921 discoveries	
	39%	81%	10%	69%

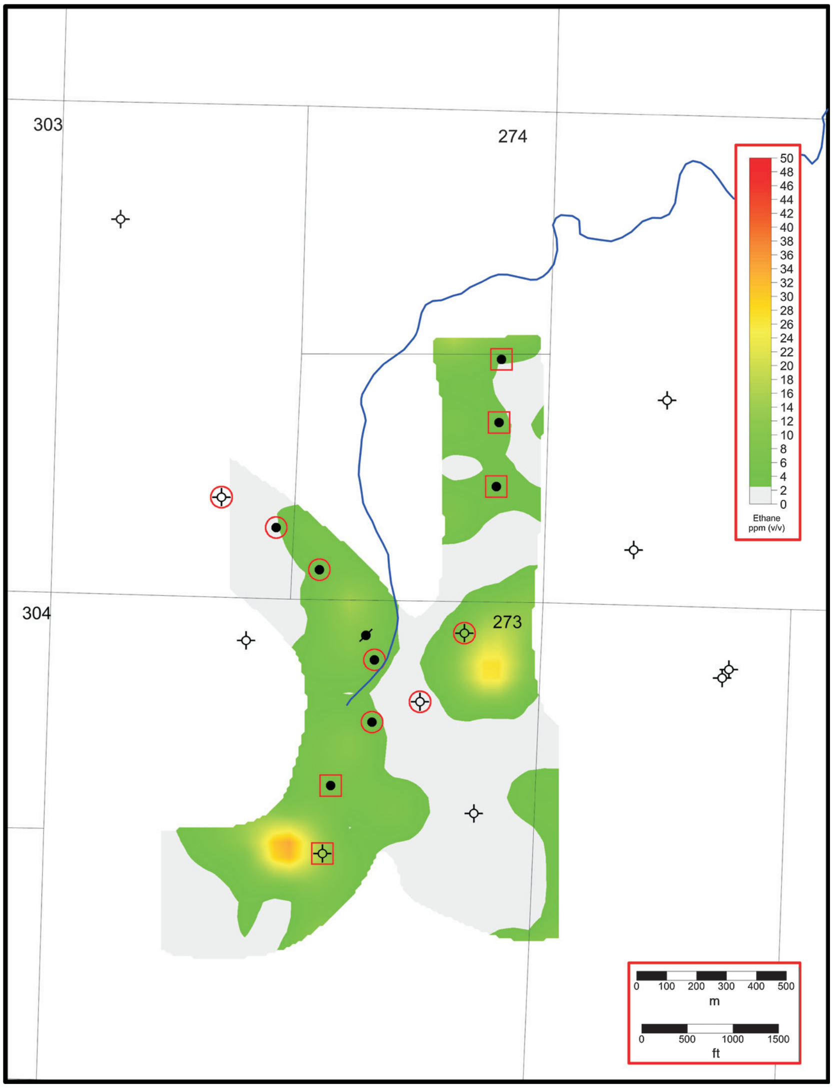


Figure 6. Postintegration drilling results. Wells in circles drilled on geology and seismic integration. Wells in squares drilled on geology, seismic, and geochemical integration.

(PW) = 71% and probability using geology + geophysics only = 35% as follows:

$$\text{PSG} = 100\% - (100\% - 71\%)/(100\% - 35\%) = 55\%. \tag{9}$$

Other stand-alone probabilities were calculated similarly.

Based on this analysis, the geochemical results, even though very good, were not solely responsible for the excellent results reported in Table 1. A significant part of the outstanding success reported in Table 1 was due to integration.

Conclusions

Probability theory predicts drilling success from integrating independent exploration data. In the case of Cheeseburger Field, actual success substantiated the calculated success using probability. Additional cases like those in Table 2 are needed for further confirmation.

This work allows us to conclude the following:

1) Elementary probability equations can be used to calculate probabilities in exploration integration.
2) Probability calculations, as presented here, are valid to the extent that the methods being integrated are independent. Stand-alone probabilities of individual methods have to be known, or reasonably estimated.
3) A simple overlay process is valid for integrating independent exploration methods because the highest probabilities will be where the methods agree.
4) Large increases in drilling success can be achieved by integrating independent exploration methods, including methods that may be moderately successful on their own.
5) Probability calculations guide exploration investment. Knowing how much a method can improve results allows calculating return on investment.

Integration is compelling. Additional methods improve the uncertainty of the other methods. Although the course of individual method improvement progresses, integration can immediately boost drilling success. Even great methods can be made better by integration. A 90% successful method can be improved to 95% by integrating with a 50% method. Although using more than one method increases cost and complexity, increased success is the benefit. Probability principles in exploration integration are a fundamental part of and lead directly to economic risk analysis. There is little reason not to integrate, and there is every reason to integrate.

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Biographies and photographs of the authors are not available.