Hydrocarbon favourability mapping using fuzzy integration: western Sverdrup Basin, Canada

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ABSTRACT

There are several difficulties in characterizing geological conditions favourable for hydrocarbon accumulation in a frontier region due to the availability and nature of geoscience data. First, geoscience information from various sources requires precise representation for spatial analysis. In many cases, the information to be represented is possibilistic or transient in nature, and it needs a mathematical tool that can adequately represent the information with a degree of possibility and/or uncertainty. Second, the uncertainty of interpreting each geological indicator and of correlating the results with physical parameters of a petroleum accumulation should be expressed explicitly. Third, the evidence and indicators of the existence of a petroleum accumulation come from various data sources, varying in degrees of uncertainty. These uncertainties should be integrated into a petroleum accumulation model so that exploration risk can be objectively evaluated in a subsequent economic analysis. We propose the use of a fuzzy integration method to tackle these problems. The method uses possibility theory to describe the satisfaction levels associated with each of the essentials for the formation of hydrocarbon deposits, such as the presence of reservoir, source rock, trap, top seal and preservation in a spatial domain. The uncertainties associated with data and evaluation are explicitly incorporated in the aggregate of the geological factors. The proposed method was applied to the Heiberg Group/Formation of western Sverdrup Basin in the Canadian Arctic Archipelago to evaluate the geological favourability for petroleum accumulation. The discovered oil and gas fields and the areas with computed high favourability display a good geographical correspondence, indicating that the proposed fuzzy integration method captures the essential spatial characteristics of petroleum accumulations in the western Sverdrup Basin.

RÉSUMÉ

Il existe plusieurs obstacles à la caractérisation des conditions géologiques favorables à l’accumulation d’hydrocarbures dans une région frontière, dû à la disponibilité et la nature des données géoscientifiques. Premièrement, l’information géoscientifique de sources diverses requiert une représentation précise pour l’analyse spatiale. Dans plusieurs cas, l’information qui doit être représentée a trait aux possibilités ou est de nature transitoire, et nécessite un outil mathématique qui peut adéquatement représenter l’information avec un degré de possibilité et/ou d’incertitude. Deuxièmement, l’incertitude quant à l’interprétation de chacun des indicateurs géologiques et quant à la corrélation des résultats avec des paramètres physiques d’une accumulation de pétrole doit être exprimé explicitement. Troisièmement, les signes et les indicateurs de l’existence d’accumulations de pétrole proviennent d’une variété de sources de données montrant des degrés divers d’incertitude. Ces incertitudes devraient être intégrées dans un modèle d’accumulation de pétrole, pour que le risque d’exploration soit évalué objectivement dans une analyse économique subséquente. Nous proposons d’utiliser la méthode d’intégration floue pour attaquer ces problèmes. La méthode utilise la théorie de la
INTRODUCTION

There are two essential processes in a petroleum exploration program: target identification and target ranking. Target identification, to evaluate and identify favourable conditions indicative of existence of oil and gas deposits, involves interpretation of geological evidence and geophysical indicators from various data sources. Target ranking involves consistent comparison amongst the available targets in terms of the likelihood of containing petroleum, the possible size of the accumulation, and the economic aspects of commercial exploitation. Since exploration targets are spatial objects and all necessary geological conditions leading to a petroleum accumulation are spatial variables, a better understanding of the factors controlling accumulation and their spatial relationship to the exploration targets is important. Geological favourability mapping is a quantitative approach for studying the spatial characteristics of favourable conditions and their relationship to the exploration targets. The resulting favourability map depicts the spatial variation of geological conditions for petroleum accumulation. This provides a consistent basis for risk analysis and target ranking, as well as exploration planning.

There are several approaches proposed for geological favourability mapping applied to exploration risk analysis and petroleum resource assessment. The play mapping methods (White, 1988, 1993; Grant and Thompson, 1996), Bayesian approach (Harff et al., 1992; Harbaugh et al., 1995), and information integration approach (Chen et al., 2000) are examples of available methods. There are problems in applying these methods to a frontier region due to the availability and nature of the geoscience data. Geoscience information from various sources requires a precise representation for spatial analysis. In many cases, the information to be represented is probabilistic or transient in nature, and the analysis needs a mathematical tool that can adequately represent the information with a degree of possibility and/or uncertainty. In a frontier region where the available geological data is regional and details or hard evidence are inadequate, it may be difficult to distinguish lack of information from negative information using a probabilistic approach. In such a setting, so-called ‘soft’ information, such as expert experience accumulated over years of exploration practice, is important for prospect generation and evaluation. The understanding of petroleum geology based on limited geoscience observations and personal experience is usually expressed in conceptual geological models or personal beliefs. These subjective judgements regarding favourable conditions or beliefs are not precise information. They commonly consist of linguistic descriptions such as good, excellent, rich or poor, the distinctive boundaries of which are unclear. Adequate representation of the linguistic variable in a quantitative fashion and the integration of this type of information together with objective observational data are difficult tasks using conventional statistical methods.

Uncertainty of interpreting each geological indicator and of correlating the results with physical parameters of a petroleum accumulation, such as interpreting seismic data (Houck, 1999) and rock physics (Mukerji et al., 2001), should be expressed explicitly. The evidence for, and indicators of, the existence of a petroleum accumulation come from various data sources and vary in degree of uncertainty. These uncertainties should be integrated into a petroleum accumulation model so that exploration risk can be objectively evaluated and explicitly expressed in subsequent prospect appraisal. A qualitative favourability mapping method, such as play mapping by White (1988) is unable to provide an effective mechanism for considering the uncertainties in such data.

Subjectivity and vagueness are two characteristics of fuzzy sets. Fuzzy sets possess useful properties for real world problems. They permit the consideration of imprecise data and can apply to a wide variety of situations. They handle ambiguous situations in a rational manner, and deal with vagueness in problems where boundaries are unclear (Chen and Fang, 1993). Fuzzy sets are applicable where geological data or information is subjective or vague. Fuzzy set theory has been applied to mineral exploration (An et al., 1991; Cheng, 1996), uncertainty management in mineral exploration (An et al., 1994; Cheng and Agterberg, 1999), prospect appraisal and ranking (Yu and Zhao, 1988; Chen and Fang, 1993), and prospect volumetric estimation in petroleum exploration (Fang and Chen, 1990).

In this paper, we propose a fuzzy integration method for geological favourability mapping with respect to petroleum accumulation in a frontier region. The method uses possibility theory to describe the satisfaction levels associated with each of the essentials for the formation of hydrocarbon deposits, such as the presence of reservoir, source rock, trap, top seal and preservation condition in a specific region. The uncertainties associated with data and in the evaluation are explicitly incorporated in the aggregation of the geological factors. As an example, the proposed method is applied to evaluating the
geological favourability for hydrocarbon accumulation in strata of the Heiberg Group/Formation of western Sverdrup Basin in the Canadian Arctic Archipelago (Balkwill and Roy, 1977; Balkwill, 1978; Embry, 1983). To be expressed in a manner more familiar to exploration risk analysis, the geological favourability derived from the fuzzy integration method is integrated with a prior probability of petroleum occurrence computed from a conventional statistical method. The resulting product, a posterior probability map, indicates the likelihood that petroleum might occur, based on the current level of available information and our knowledge in this region, which in turn provides a consistent rationale of target ranking for a particular petroleum play.

**Method Description**

Fuzzy methods have been proposed for prospect appraisal (e.g. Yu and Zhao, 1988; Chen and Fang, 1993) and prospect volumetric estimation (Fang and Chen, 1990) in petroleum exploration. Prospects are spatial objects and prospect comparison in target ranking can be consistently handled across the region of a petroleum play using a fuzzy method. The proposed method is an extension of the prospect appraisal methods used by Yu and Zhao (1988). In a spatial domain, a geological factor (or variable) is represented by \( N \) rectangular pixels in the mapping area. The value on the map can be numerical (in quantitative form, such as a formation thickness) or symbolic (in qualitative form of a conceptual geological model, such as a depositional facies). Suppose that there are \( I \) geological factors being considered in a favourability evaluation. At pixel \( j \) on the \( k \)-th geological map, \( x_{kl}(j) \) is defined to represent the average value of the geological variable, such as the formation thickness, or a dominant geological feature, such as a type of depositional facies. The geological favourability of hydrocarbon occurrence at each untested location is evaluated using the fuzzy integration method based on the \( I \) geological variables. The evaluation consists of the following six steps:

1. **Preparation of favourability diagrams and membership functions.**
   
   Favourability of a geological factor with respect to petroleum accumulation is represented by a fuzzy set, in which degrees of membership are defined. In a fuzzy set, an element may or may not be completely in or out of the set, so it is given a degree of membership. Figure 1 shows that the degree of membership varies with measured reservoir porosity for the category of "a good reservoir". In this example, reservoir porosity in clastic strata equal to and larger than 15% is clearly a good reservoir (membership 1), porosity less than 8% is definitely not a good reservoir (membership 0); whereas porosity between 8–15% is some sort of good reservoir with a varying degree of membership. In this study, five categories of evaluation level (excellent, good, fair, poor and very poor) are used. For each category, a membership function is defined to express the appraiser’s beliefs of the degree of favourability. Since defining a membership function is often arbitrary and difficult (An et al., 1991), we chose to use a simple form of membership function (Table 1). In Table 1, the favourability of a geological factor is classified into five levels, from the worst, 0 to the best, 1.0. The membership is represented by a value from 0 to 1. For the excellent category, the degree of membership is pointing to a high degree of favourability; in contrast, in the most unfavourable condition, the degree of membership is pointing to the lowest degree of favourability. In many ways, this table represents approximations to some of the membership functions proposed by Zadeh (see Chen and Fang, 1993).

2. **Selection of geological factors and sub-factors.**
   
   Geological factors (variables) are selected to represent the major geological controls on the spatial occurrence of petroleum deposits, such as source rock, trapping condition and reservoir rock. A geological factor may have several sub-factors. For example, a geological factor of reservoir quality can be described by several sub-geological factors such as porosity, thickness, depositional facies and permeability. Table 2 lists some examples of the geological factors and sub-factors used in this study. Modifications of the selected geological factors and sub-factors can be made to reflect the assessor’s beliefs and the company’s exploration goals. Data availability is also a factor affecting the selection of the geological factors and sub-factors. Geological factors controlling the formation of petroleum accumulation are not necessarily the same as those controlling their spatial distribution.

3. **Determining evaluation criteria sets.**
   
   Evaluation criteria must be determined to describe the relationship between geological evidence (or conditions) and their corresponding favourability levels with respect to hydrocarbon accumulation in the area of interest. A geologist or a group of geologists working individually or collectively arrive at a list of criteria for the geological favourability evaluation. For example, Table 3 lists some of the criteria used in this study. The criteria set may vary in different geological settings or exploration environments, depending on the geologists’ beliefs and the company’s risk tolerance or exploration goal.

![Fig. 1. An example showing how the degree of membership varies with the measured porosity in a reservoir for a “good reservoir”.](image-url)
(4) Assessing relative importance of geological factors. Certain geological factors may have greater relative importance with respect to geological favourability. We introduce weights to describe the relative importance for each of the geological factors. The number of weights should be the same as the number of geological factors. The sum of all weights must be a unity. For each subset of the geological factor, we have corresponding sub-weights. The sum of all weights for the sub-factors must be a unity. The weights are usually determined subjectively by a group of geologists working in the area, and these reflect their understanding of the relative importance of different geological factors with respect to the spatial

<table>
<thead>
<tr>
<th>F.L.</th>
<th>E.Categ</th>
<th>0</th>
<th>0.25</th>
<th>0.5</th>
<th>0.75</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
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<td>0</td>
<td>0</td>
<td>0.25</td>
<td>1.0</td>
</tr>
<tr>
<td>V2</td>
<td>Good</td>
<td>0</td>
<td>0</td>
<td>0.35</td>
<td>1.0</td>
<td>0.35</td>
</tr>
<tr>
<td>V3</td>
<td>Fair</td>
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<td>1.0</td>
<td>0.35</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>V4</td>
<td>Poor</td>
<td>1.0</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

F.L. — Favourability level, E. Categ — Evaluation category

Table 1. Membership functions for five valuation levels.

<table>
<thead>
<tr>
<th>Geological variables</th>
<th>Symbol G_{rk}</th>
<th>Possible condition set (A_{rk})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source rock</td>
<td>(G_1)</td>
<td>{very poor, poor, fair, good, excellent}</td>
</tr>
<tr>
<td>Quality</td>
<td>(G_{11})</td>
<td>{very little, little, fair, rich, very rich}</td>
</tr>
<tr>
<td>Quantity</td>
<td>(G_{12})</td>
<td>{Not mature, low mature, mature, high mature, over-mature}</td>
</tr>
<tr>
<td>Maturity</td>
<td>(G_{13})</td>
<td>{absent, thin, fair, thick, very thick}</td>
</tr>
<tr>
<td>Net/Gross</td>
<td>(G_{24})</td>
<td>{absent, minor, fair, active, very active}</td>
</tr>
<tr>
<td>Top Seal</td>
<td>(G_{3})</td>
<td>{absent, thin, medium, thick, very thick}</td>
</tr>
<tr>
<td>Thickness</td>
<td>(G_{32})</td>
<td>{absent, thin, medium, thick, very thick}</td>
</tr>
<tr>
<td>Preservation</td>
<td>(G_{4})</td>
<td>{very active, active, fair, inactive, absent}</td>
</tr>
<tr>
<td>Post-volcanism</td>
<td>(G_{41})</td>
<td>{very small, small, medium, large, very large}</td>
</tr>
<tr>
<td>Vertical migration</td>
<td>(G_{6})</td>
<td>{abundant, many, a few, one or two, none}</td>
</tr>
<tr>
<td>Trap</td>
<td>(G_{61})</td>
<td>{non, may be, pillow, diapir, pierced diapir}</td>
</tr>
</tbody>
</table>

\(G_{rk}\) — Geological variables
occurrence of petroleum accumulations. The weights can be derived objectively from a quantitative data matrix using the eigenvector method (Jin, 1989).

(5) Fuzzy integration computation. There is a fuzzy mapping between the observed or inferred geological evidence and the geological favourability level. The verbal statements in Table 3 are translated into mathematical representations using the membership functions for each element of the fuzzy set, and they are combined to arrive at individual evaluation functions for each appraisal. In the evaluation, the geological factors are subdivided into two groups: necessary factors and preferable factors. A necessary factor represents a prerequisite condition for the presence of a hydrocarbon deposit at a given location. For example, the presence of a reservoir is a prerequisite condition for forming a petroleum deposit, and it is therefore classified as a necessary factor. In contrast, the presence of a fracture is a preferential factor. The presence of the fracture could enhance reservoir permeability, resulting in a favourable condition for hydrocarbon accumulation. However, hydrocarbon accumulation can still occur without the development of the fracture. Two different fuzzy operators are applied to these two factor groups. For the necessary factor, we use a minimum operator. This operator guarantees the output result meeting the prerequisite conditions for hydrocarbon occurrence, reflecting the fact that the lack of any necessary condition will lead to a failure to form a hydrocarbon deposit. For example, if we have a perfect source rock \((a = 1)\), but lack of reservoir rock \((b = 0)\), the minimum operator results in \(c = 0\), indicating no condition for petroleum accumulation (see Appendix). This operator also reflects the bottleneck effect: given that hydrocarbons exist in a region, the relative favourable condition is determined by the poorest factor in the hydrocarbon accumulation processes. For example, if the preservation condition is poor and the reservoir condition is excellent, then the favourability for petroleum accumulation is poor. For the preferential factors, we use a sum of multiplication operator. This operator takes different weights for different geological factors, thus allowing different geological factors with various impacts on petroleum accumulation to be integrated according to their relative importance (see Appendix). The final results of such an evaluation at a given location is expressed neither as a single value, nor as a range of estimates, but as a fuzzy set. We cannot put a fuzzy set on a geological map, so the final result in this study is expressed as a favourability score that measures the relative distance from the least favourable condition (Equation 9 in Appendix).

(6) Information updating. A geological favourability map alone provides a quantitative measure of relative favourability in a region of interest, a useful measure in play and prospect evaluation. A probability expression of uncertainty is more convenient in risk analysis and prospect ranking. The favourability map can be integrated with another type of data, such as exploration drilling outcomes, and expressed in a more familiar fashion as a probability. Since the geological favourability map is derived from geoscience observations and subjective judgements using fuzzy integration, it is independent from the exploratory wildcat drilling results. A prior probability map of petroleum occurrence calculated from exploration drilling results is updated by the geological favourability map, resulting in a posterior probability. The posterior probability map is a convenient measure of risk analysis for exploration planning and prospect ranking (Chen et al., 2001). Chen et al. (2000) discussed the method of computing the prior probability of petroleum occurrence. For a detailed description of the fuzzy integration method for prospect evaluation the reader is referred to Yu and Zhao (1988) and Chen and Fang (1993). The appendix provides a brief description of the algorithms for the fuzzy integration used in this study.

### AN APPLICATION EXAMPLE

**GEOLOGICAL SETTING**

The Sverdrup Basin is a major extensional basin underlying the Queen Elizabeth Islands of the Canadian Arctic Archipelago. Petroleum exploration occurred in the Sverdrup Basin between 1969 and 1986. Over this time period 119 wells were drilled and 19 hydrocarbon fields, consisting of eight oil and 25 gas pools, were discovered. Estimated total, in place reserves are \(294.1 \times 10^{6} \) m³ oil and \(500.3 \times 10^{9} \) m³ gas (Chen et al., 2000). Unfavourable external factors, primarily global economics and infrastructure costs, ended exploration activities despite extraordinary exploratory success. The discovered petroleum fields all occur within a broad fairway extending from western Ellef Ringnes Island southwestward to northeastern Melville Island (Fig. 2) and are accumulated in structural traps. The Sverdrup Basin succession, up to about 13,000 m

<table>
<thead>
<tr>
<th>Variables</th>
<th>V. Poor</th>
<th>Poor</th>
<th>Fair</th>
<th>Good</th>
<th>Excellent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Richness</td>
<td>TOC&lt;0.8</td>
<td>0.8&lt;TOC&lt;1.0</td>
<td>1.0&lt;TOC&lt;2.0</td>
<td>2.0&lt;TOC&lt;3.0</td>
<td>TOC&gt;3.0</td>
</tr>
<tr>
<td>Quality</td>
<td>Type IV</td>
<td>Type III+IV</td>
<td>Type III+II</td>
<td>Type II+I</td>
<td>Type I</td>
</tr>
<tr>
<td>Maturity</td>
<td>Ro&gt;3.5</td>
<td>Ro=2.5-3.5</td>
<td>Ro=2.0-2.5</td>
<td>Ro=1.5-2.0</td>
<td>1.5&gt;Ro&gt;0.9</td>
</tr>
<tr>
<td>Porosity</td>
<td>ϕ&lt;5%</td>
<td>5%&lt;ϕ&lt;8%</td>
<td>8%&lt;ϕ&lt;12%</td>
<td>12%&lt;ϕ&lt;20%</td>
<td>ϕ&gt;20%</td>
</tr>
</tbody>
</table>

Table 3. Example of evaluation criteria for geological factors.
thick, comprises Carboniferous to early Tertiary marine and non-marine strata. Oil and gas accumulations found to date are present mainly in the uppermost Triassic–Lower Jurassic porous sandstone of the Heiberg Group beneath thick argilla-
ceous strata of the Jameson Formation (Fig. 3).

The regional petroleum geology has been summarized by Embry (1991) and Waylett and Embry (1993). The stratigraphy and structural geology of the area are described by Balkwill and Roy (1977), Balkwill et al. (1982), Balkwill (1983), Embry (1991) and Harrison (1995). Internally, the basin is deformed both by diapiric structures developed accompanying the episodic flow of Carboniferous evaporites (Balkwill, 1978) and by Barremian to Cenomanian basaltic volcanism and diabase intrusions (Emery and Osadetz, 1988). In the Eocene, and subsequently, Sverdrup Basin was deformed during Eurekan orogeny. The structures formed in this period include high amplitude folds and thrust faults (Harrison et al., 1999). The effects of Eurekan orogenesis are intense in northeast Sverdrup Basin and subdued in the southwest (ibid). The combination of reservoir diagenesis, influenced by magmatism during the early Cretaceous to earliest late Cretaceous rifting phase, and the differences in structural history and style partition the Sverdrup Basin. A region of reduced petroleum potential occurs in eastern Sverdrup Basin, specifically Axel Heiberg and Ellesmere islands, where the effects of Mesozoic magmatism and Tertiary deformation are the strongest. In the eastern Sverdrup Basin, a generally deeper erosional level has removed or breached the most prospective reservoir strata in many structures. A region of higher petroleum prospectivity occurs in western Sverdrup Basin, west of Nansen Sound, where the volume of Cretaceous magmatism and its impact on reservoir diagenesis is reduced. The generally higher erosional level in western Sverdrup Basin preserves Triassic to Lower Cretaceous reservoir formations in a region where structure is dominated by lower amplitude folds, many of which are cored by evaporites.

The primary effective source rocks in the Sverdrup Basin are bituminous marine shales in the Middle to Upper Triassic Schei Point and Blaa Mountain groups (Powell, 1978; Brooks et al., 1992). The richness of total organic carbon (TOC) appears to be controlled by depositional environment (Fig. 4; and compare with Fig. 12.29 in Embry, 1991). The western Sverdrup Basin encompasses a wide range of source rock maturity, from immature on the basin edges to over-mature in the basin centre. Most of the strata reached or passed through the maturity window from late Early Cretaceous to latest Cretaceous (Brooks et al., 1992; Goodarzi et al., 1993). The main stage of petroleum generation occurred generally between late Early Cretaceous and latest Cretaceous time (Brooks et al., 1992; Goodarzi et al., 1989; 1993). Figure 5 is a map of Tmax from Rock-Eval analysis, displaying the spatial variation of the source rock maturity.

Secondary migration in this basin is complicated, perhaps involving re-migration of some reservoired hydrocarbons (Waylett and Embry, 1993). Vertical migration pathways and

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**Fig. 2.** Location of the study area and exploration results in the western Sverdrup Basin, Canadian Arctic Islands. Locations are described using latitude and longitude. Subsequent maps display the same region using Lambert project (CM: 111.5º, base lat.: 49º, Lambert lower std. lat.: 49º, Lambert higher std. lat.: 77º) for computational convenience. Black areas indicate discovered oil and gas fields.
seepage are indicated by stacked pools in a number of structures, while oil staining is common in water-bearing structural closures as well as gas fields (Gentzis and Goodarzi, 1993). The lack of complete spatial correspondence between the maturity of oils and source rocks (Fig. 5) indicates that basin uplift, re-migration of pre-trapped hydrocarbons, and localized source rock maturity variation due to igneous intrusions and salt structure emplacements are factors responsible for the maturity discrepancies between source rocks and oils (Curiale, 1992). This explanation is supported by the fact that measured oil maturity shows a better correlation with present-day reservoir temperature.

Heiberg sandstones, a major fluvial-deltaic deposit with thickness varying between over one thousand metres in the basin centre and a feather-edge on the basin flanks, are the primary reservoirs (Fig. 6) (Embry, 1983). Figure 7 shows the average porosity in the Heiberg Group derived from well logs.
and core analysis of the reservoir with discoveries. The reservoir porosity appears to be good along the southern flank of the basin as well as the Maclean Strait area. The porosity becomes unfavourable in the northeast due to deep burial and diagenesis, and in the northwest due to unfavourable depositional facies. **Data Analysis**

Several types of geological data have been collected from published literature and our own analysis for this study. These include the geological factors controlling the formation of...

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**Fig. 5.** Present-day source rock maturity for the Schei Point source rock strata (based on data from Brooks et al., 1992 and Goodarzi et al., 1993). Crosses indicate well control, and triangles indicate oil maturity measurements (Curiale, 1992). Green: less mature; brown: mature; and pink: most mature. The colour bar in the right indicates the Tmax contour values in degrees Celsius.

**Fig. 6.** Net sand/gross thickness ratio of the Heiberg Group, western Sverdrup Basin. The colour bar at right indicates the net/gross contour values.
petroleum accumulations and exploration outcomes revealing the magnitude and spatial variation of petroleum accumulations in the play. The geological data have been grouped according to their roles in petroleum accumulation. The available source rock data mainly come from organic geochemistry analysis of hand-picked cuttings and core samples from recognized source rocks (Brooks et al., 1992; Goodarzi et al., 1989; Powell, 1978), and biomarker maturity parameters of discovered oils (Curiale, 1992). Geological data regarding reservoir quality include reservoir thickness, net sand/shale ratio, and estimated average reservoir porosity. For structural trap data, we have a two-way seismic travel time map to the top of Heiberg Group and the thickness of top seal (Jameson Bay Formation). Information with respect to preservation of petroleum accumulation includes existence of faults on top of the Heiberg Group, relative abundance of post-hydrocarbon-generation volcanic extrusions and sills, and salt diapirs within the reservoir interval. The exploration results comprise well locations of oil and gas discoveries as well as dry holes (Fig. 2), and the sizes of discoveries. Other exploration information, such as borehole temperature, water salinity and pressure measurements from DST tests are also available. Secondary information derived from the original data includes a structural map from seismic travel time using Bayesian Cokriging (Doyen et al., 1996), pressure gradient, hydraulic potential, magnitude of post-generation uplift and structure residuals, etc. Most available primary data used in this study are listed in Table 2.

Since tangible observations are sparse, subjective judgments from geologists form an important part of the information integration and decision making process. A good understanding of the geological framework and its control on oil and gas accumulation in this region is therefore essential in the fuzzy integration. Effort has been made to study the role that each individual geological element played in forming the spatial characteristics of petroleum accumulations. Analysis of the spatial correlation between each geological factor and petroleum occurrence is helpful in determining the relative importance of each geological element. For example, a comparison of the spatial distribution of source rock richness to the locations of oil and gas fields shows a limited correlation, indicating that the spatial variation of source rock richness is not a key factor controlling the location of petroleum accumulation, even though the presence of an effective petroleum system is a necessary condition for petroleum occurrence. However, as will be seen below, because vertical migration dominated secondary migration in the Sverdrup Basin, the spatial extent of the mature source rock determines the spatial limits of oil and gas fields.

**GEOLOGICAL FAVOURABILITY MAPPING**

Following the procedures described in the previous section, geological indicators (observed and inferred) are converted into an evaluation matrix using membership functions (Table 1) and evaluation criteria (Table 3). The evaluation matrices are integrated, first by a minimum operator for the necessary geological factors and then by a sum of production for the preferential factors, into a fuzzy set. The evaluation procedure is applied to the sub-factor level, deriving a fuzzy evaluation set for individual geological factors first, then at the factor level to obtain a final geological favourability map. This computation is carried out at every pixel for the entire study area, and the
evaluation fuzzy sets are then projected as a distance in the Euclidean space at each pixel, reflecting the relative favourability level.

Figure 8 illustrates the reservoir quality at a factor level by integrating available sub-geological factors relevant to the overall quality of the reservoir rock in this region. Four sub-factors—depositional facies, net-sand thickness, net/gross ratio and average porosity of the reservoir—are considered in the evaluation. It appears that the reservoir quality computed from the fuzzy integration method is realistic since all discovered fields are located in the areas with favourable reservoir condition. Some of the dry structures could be a result of missing quality reservoir in the northeast and northwest areas. In contrast, the overall source rock quality (Fig. 9), a comprehensive indicator of TOC richness, quality of organic matter (Hydrogen Index) and maturity of source rock (Tmax), does not show a convincing geographical correspondence with the discovered oil and gas fields. This is because the location where oil and gas are generated is not necessarily the location where oil and gas are finally trapped, as secondary migration and possible re-migration redistributed the oil and gas after their expulsion from the source rocks.

Other geological factors, such as preservation conditions (characterized by the presence of faults in the Heiberg Group, evidence of extensive igneous intrusion activity, reservoir pressure gradient, top seal thickness and post-generation uplift), conceptual rifting model (Balkwill and Fox, 1982) and structural characteristics (structural residuals) are evaluated separately and subsequently integrated with the reservoir and source rock qualities to produce an overall geological favourability map (Fig. 10).

The geological favourability map, combining information from both geoscience observations and subjective judgements, represents a quantitative measure of relative favourability with respect to petroleum accumulation. A comparison of the favourability map with the spatial occurrence of discovered oil and gas fields shows a good geographical coincidence. In areas where the geological favourability score is smaller than 0.8, there are no discoveries. In contrast, there are 39 discovery wells and 34 dry wells located in the areas where the favourability score is greater than 0.8, a success rate of 53%. In the area where the favourability score is greater than 1.25, the number of discovery wells is 27, and the number of dry wells is 11, a success rate of 69% (Fig. 11). It appears that the geological favourability indicates not only the favourable condition for the presence of petroleum accumulation, but also the relative abundance of the petroleum resource. More than 85% of the discovered reserves are found in the most favourable area (the favourability score value >1.25). It is therefore reasonable to infer that the geological favourability map also contains information regarding undiscovered oil and gas accumulations.

A prior probability map of petroleum occurrence, outlining the likelihood of spatial occurrence of petroleum accumulations, can be computed from previous exploration drilling results. From a statistical point of view, observations from exploration drilling represent a biased sample because selection of exploration drilling sites is not random, but deliberate. However, the probability map is derived from real observation of petroleum accumulations. On the other hand, the geological favourability mapping uses different data sources (geological evidence and indirect indicators of petroleum accumulation)
and is independent from exploration drilling results. The prior probability map can therefore be improved by including additional information in the geological favourability map. This is accomplished by updating the prior probability of hydrocarbon occurrence by the geological favourability map using Bayesian techniques (see Chen et al., 2000 for the method). Thus the resulting map in Figure 12, a posterior probability of hydrocarbon occurrence, contains information from both geological evidence and exploration drilling outcomes, and represents an improved picture of the spatial characteristics of petroleum

Fig. 9. Source rock favourability map derived from integrating all available source rock data, Schei Point Group. Original data compiled from Brooks et al. (1992), Goodarzi et al. (1993) and Powell (1978). The colour bar at right indicates the source rock favourability score contour values.

Fig. 10. Overall geological favourability map derived by integrating reservoir quality, source rock quality, preservation condition and structural characteristics. The colour bar at right indicates the overall geological favourability score contour values.
accumulations. It is also a useful measure in risk analysis and prospect ranking.

**Discussion and Conclusions**

In a frontier basin, such as the western Sverdrup Basin, ‘hard’ data from exploration activities are scattered. Therefore, the inferred geological models and personal beliefs based on experience obtained during exploration are important information sources in prospect generation and evaluation. We illustrated that the fuzzy integration method makes it possible to integrate hard evidence and personal beliefs quantitatively to derive a geological favourability map of petroleum accumulations in a region of interest. The discovered oil and gas fields and the areas with computed high favourability display a good geographical correspondence. This indicates that the fuzzy integration method captures the essential spatial characteristics of petroleum accumulations.

Many activities, such as play analysis, resource evaluation, project ranking, and decision making involve risk evaluation. An expression of probability is a more convenient and direct measure of risk. We have shown, in the example, that the computed geological favourability can be easily integrated with exploration results to produce a posterior probability map of petroleum occurrence using a Bayesian approach. This map is a comprehensive quantitative measure of the likelihood of petroleum occurrence in a region of interest.

The fuzzy integration method allows the integration of different types of information in a quantitative way, and allows the synthesis of a petroleum accumulation model for exploration in a frontier region where details of geoscience information are imperfect. Variations in subjective judgements could result in an alternative outcome. Each hypothesis can be tested by altering the subjective judgements to see the consequences of different interpretation scenarios. In this sense, the fuzzy integration method is a tool for hypothesis testing.

Because geological sub-factors are integrated to represent a single geological factor in the integration process, the proposed fuzzy approach is a useful tool for the analysis of relative

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**Fig. 11.** Plot showing the relationship between the number of occurrences and corresponding geological favourability values for dry and discovery wells, respectively. Thick solid line represents the discoveries, and the thin solid line represents dry wells.

**Fig. 12.** A posterior probability map of petroleum occurrence for the Heiberg Group, western Sverdrup Basin, produced by updating a prior probability derived from exploration drilling results with the geological favourability map in Figure 10. The colour bar at right indicates the posterior probability contour values.
importance of individual geological factors with respect to petroleum occurrence. The determination of relative importance of each individual geological element is an interactive process in the integration procedure. Close examination of the spatial relationship between the computed favourability of individual geological factors with real oil and gas occurrence will reveal the most important factors that control the spatial distribution of petroleum accumulations. Addressing the most important geological factors and reducing the uncertainties associated with them are effective ways for improving exploration efficiency.

The fuzzy integration method handles subjective information in a subjective manner. The determinations of relative importance of the geological elements, evaluation criteria of geological variables as well as the membership functions require expertise not only in petroleum geology, but also in data analysis. A good understanding of regional petroleum geology is crucial for an improved view of the spatial distribution of undiscovered petroleum accumulations. It should be noted that using the proposed method, the geoscience information from observed and inferred data as well as personal beliefs are integrated to outline a comprehensive picture of the favourable conditions for hydrocarbon occurrence. The result is a projection from our current understanding of the petroleum geology based on the available geoscience information. The result should be updated when new data are available or as understanding of the petroleum geology in the area improves.

In conclusion, the clear association between exploratory success and large values of favourability, determined by this method, shows that it provides a useful tool for the integration of subjective information into the exploratory decision making process.

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APPENDIX

FUZZY SET AND FUZZY OPERATORS

A fuzzy set of \( A \) is a set of ordered pairs (An et al., 1991):

\[
A = \{ [x, \mu_A(x)] | x \in X \}
\]

where \( X \) is a collection of objects and \( \mu_A(x) \) is called the membership function of \( x \) in \( A \). \( \mu_A(x) \) maps \( X \) to the membership space. A membership function is defined over a universe of discourse \([0,1]\). Differing from the ordinary set, the fuzzy set allows partial membership. In other words, as well as the membership degree of 0 and 1, membership degrees between 0 and 1 are permitted. Figure 1 depicts various values of measured porosity and their corresponding degree of membership with respect to a “good reservoir”.

As fuzzy sets are sets, they have different set operations. Let \( A \) and \( B \) be fuzzy sets, and \( \mu_A(x) \) and \( \mu_B(x) \) be their corresponding membership functions. The following are the most commonly used operators:

- **A)** Maximum (Union) of \( A \) and \( B \):
  \[
  \max[\mu_A(x), \mu_B(x)]
  \]

- **B)** Minimum (Intersection) of \( A \) and \( B \):
  \[
  \min[\mu_A(x), \mu_B(x)]
  \]

For matrix operation, the sum of production operator (Yu and Zhao, 1988) is used in this study:

\[
C_j = \sum_{i=1}^{n} w_i r_{ij} \quad j = 1, 2, \ldots, m
\]

where \( w_i \) is a weight in (6) and \( r_{ij} \) is the \( ij^{th} \) element in (8).

FUZZY INTEGRATION PROCEDURE

Let \( X_i \) denote the \( ith \) geological factor and \( V_i, i=1,2,\ldots,p \) be the \( p \) evaluation categories.

A set of geological factors is written as:

\[
X = \{X_1, X_2, \ldots, X_n\}
\]

For each geological factor, it may have \( m \) sub-factors that contribute to the overall feature of the geological factor. Because each geological factor may have different impacts on hydrocarbon occurrence in

\[
X_i = \{X_{i1}, X_{i2}, \ldots, X_{im}\}
\]

a petroleum play, we introduce a weighting \( W \) to account for the differences. This would be the compensation parameter in An et al. (1991). The number of weights must be equal to the number of geological factors and the sum of the weights must be unity. That is:

\[
W = \{W_1, W_2, \ldots, W_n\}
\]

and

\[
\sum_{j=1}^{n} W_j = 1
\]

The same applies to the sub-factors:

\[
W_i = \{W_{i1}, W_{i2}, \ldots, W_{in}\}
\]

and

\[
\sum_{j=1}^{n} W_{ij} = 1
\]

Mapping from geological evidence to geological favourability space through the membership function (the evaluation criteria matrix in this study) results in an evaluation matrix \( R \):

\[
R = \begin{bmatrix}
  r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\
  r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\
  \vdots & \vdots & \vdots & \vdots & \vdots \\
  r_{n1} & r_{n2} & r_{n3} & r_{n4} & r_{n5}
\end{bmatrix}
\]

(8)

The minimum operator is applied to integrate the geological factors representing the necessary conditions for occurrence of hydrocarbons. The multiplication and summation operator is then used to integrate the preferable geological sub-factors and factors into a single matrix \( A \), representing a fuzzy set of evaluation results of the geological favourability. For the convenience of Bayesian information updating, the resulting favourability is projected as an Euclidean distance by the following operation:

\[
D = AC^T
\]

(9)

where \( C \) is the Euclidean distance vector (also called favourability score in this study) and is defined as \( C^T = \{0, 0.25, 0.5, 0.75, 1\} \) in this study.