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Identifying productive zones of Sarvak formation by integrating outputs of different classification methods

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Abstract
Sarvak formation is the second major carbonate reservoir in Iran. There are several geological, petrophysical and geophysical investigations which have been carried out on this important reservoir. In this work, Sarvak is studied to find productive zones. At first, four different methods were used to identify producing intervals from well log data and well test results. Then, final zoning is generated by integrating outputs of these four methods. One of them is the conventional cut-off-based method; the other three methods are based on flow equation, Bayesian and fuzzy theories. Thereafter, by considering the classification correctness rate of each classifier in each well and technique of majority voting, a unique zoning for Sarvak formation is presented. Based on the final zoning, the whole Sarvak interval is divided into seven zones. Three of them are classified as oil producing zones, two of them cannot be classified as conventionally producing zones, and the remaining two are water producing. Zone number 2 not only has the highest production rate, but also is the most homogeneous zone among the productive zones. The novelty of this research is using well test results in defining productive classes, which improves the certainty of classification in comparison with previous works that were based on core analysis and log data.

Q1 **Keywords:** Sarvak formation, carbonate reservoir, productivity, pay zone, zoning, data fusion

Q2 (Some figures may appear in colour only in the online journal)

1. Introduction

Sarvak is a carbonate reservoir rock, deposited during Middle Cretaceous. Probably the first geologists who published a paper about Sarvak formation were James and Wynd. In this paper, two members of Sarvak formation were identified (James and Wynd 1965). There are lots of investigations on Sarvak formation (and its equivalents, especially Mishrif) from different points of view. Here, some of the recent research works, most relevant to this work, are presented.

In 2007, by integrating seismic and well log data, a 3D static model of the Mishrif reservoir (upper Sarvak) was created in Sirri district, the Persian Gulf. According to the static model, it was concluded that a gradual transition exists between Khatiyeh (a basinal deposition facies, equivalent to middle Sarvak) and Mishrif facies but the transition zone varies in thickness (Bashari 2007b). Bashari has completed another investigation about the Mishrif reservoir in the Reshadat oil field, the Persian Gulf. In this study, seismic, petrophysical and petrographical data were combined to create a static model of Mishrif, and then, reservoir quality, thickness variation and lateral facies changes of Mishrif were discussed (Bashari 2007c). Q3 Q4

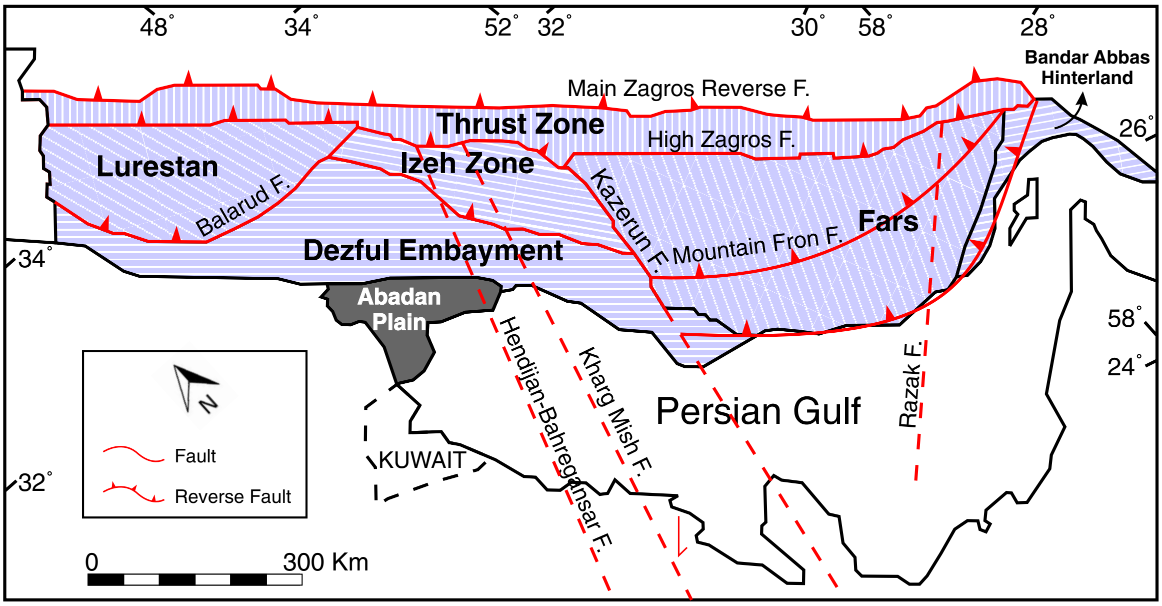


Figure 1. Locationof Abadan Plain is illustrated in Zagros. Modified after Sherkati and Letouzey (2004) and Rajabi *et al* (2010). Q5

Another valuable work was carried out in the same year by Taghavi *et al*. As an output of this paper, upper Sarvak is classified into eight different flow units in the Dehluran field, SW Iran. This classification is obtained from evaluating the heterogeneity of petrophysical parameters, after assessing the heterogeneity and distribution of geological variables. Out of these eight distinguished flow units, two (FU3 and FU6) belong to grain-supported shoal/reef deposits with good reservoir qualities. FU1 and FU4 are related to leached lagoonal deposits, the main pore types of which are vuggy or micropores, and represent medium reservoir quality, and the remaining four are non-producing flow units (FU2, FU5, FU7 and FU8) (Taghavi *et al* 2007).

In 2009, a comprehensive study was conducted by Shahvar *et al* about predicting permeability in Sarvak formation from different aspects. They predicted a flow zone index (FZI) using fuzzy logic and well log data. Then, the FZI approach was applied for reservoir rock typing and defining hydraulic units. Thereafter, an artificial neural network (ANN) was utilized to estimate the permeability of Sarvak formation in each of its hydraulic unit separately. Permeability was also identified by a conventional regression-based method. Finally, they concluded that the conventional method is not as robust as the intelligent one in predicting the behaviour of heterogeneous carbonate reservoirs (Shahvar *et al* 2009).

There are some other research works on this reservoir rock which have studied several properties of Sarvak regarding several viewpoints. In 2009, Al-Ameri *et al* analysed the biomarkers, palynofacies and pyrolysis results of the Mishrif reservoir in Zubair and both Rumaila North and South fields, Kuwait area, and found the source rock of this reservoir in
Q6 Upper Jurassic Formations (Al-Ameri *et al* 2009). However it is claimed by Bashari that in the Persian Gulf oil fields, the source rock of Mishrif belongs to Middle Cretaceous sediments: in the Fateh, Sirri A, Sirri C and Sirri D fields, basinal Khatiyah sequences form the source rock for the Mishrif reservoir, and in the Hendijan field, hydrocarbon generation occurs in the Kazhdumi Formation (Bashari 2008). A detailed stratigraphic survey is carried out on the outcrop of Sarvak formation in Bangestan anticline, Iran. The most important result of this research is the classification of this shallow deposited carbonate formation into 12 microfacies classes, and relating these facies to the corresponding sedimentary environments: inner shelf (lagoon), middle shelf, outer shelf and basin (Ghabeishavi *et al* 2010). Piryaei *et al* have conducted two comprehensive studies on the late Cretaceous tectono-sedimentary processes in the Fars region, which includes Sarvak formation (Piryaei *et al* 2010, 2011). Q7

Here, a zoning on the whole Sarvak interval is presented regarding the production rate. The article, published by Taghavi *et al* (2007), is closely related to the current work. They have classified only upper Sarvak into different flow units by analysing geological and petrophysical raw data, whereas here, the whole Sarvak is classified into different producing zones due to production rates, derived from well tests.

2. Geological setting

This investigation is applied on the Sarvak interval of six wells, drilled on an anonymous field in the Abadan Plain, SW Iran (figure 1). The gross interval of Sarvak in these six wells varies approximately from 590 to 670 m, and is restricted to the Khazhdumi and Laffan Formations from bottom and top, respectively (figure 2).

Sarvak formation (Upper Albian to Upper Turonian) is an important carbonate reservoir of Bangestan Group, and stratigraphically is equivalent to Mauddud, Khatiyah and Mishrif sequences in the Persian Gulf (Bashari 2007a). Simplified stratigraphy of Cretaceous is presented in figure 2. A detailed stratigraphic study has revealed that Sarvak is deposited on a shallow carbonate shelf setting. Moreover, generally, younger parts belong to shallower environments

Table 1. Summary of datasets, available for this work. 'npv' stands for 'net pay value'. npv = 1 shows that the well test interval is not oil producing, npv = 2 reveals that the tested interval is oil producing but less than 1500 barrels per day and npv = 3 means that the well test result shows oil production more than 1500 barrels per day.

		Well 1	Well 2	Well 3	Well 4	Well 5	Well 6
No of well test intervals	npv = 1	3	2	4	1	×	1
	npv = 2	3	×	1	1	×	×
	npv = 3	×	1	1	1	×	3
Petrophysical well logs	Caliper (CALI)	✓	✓	×	✓	✓	✓
	Gamma ray (GR)	✓	×	✓	✓	✓	✓
	Corrected gamma ray (CGR)	✓	✓	✓	✓	✓	✓
	Sonic log (DT)	✓	✓	✓	✓	✓	✓
	Neutron porosity (NPHI)	✓	✓	✓	✓	✓	✓
	Bulk density (RHOB)	✓	✓	✓	✓	✓	✓
	Density correction (DRHO)	✓	×	✓	✓	×	×
	Deep laterolog resistivity (LLD)	✓	✓	✓	✓	✓	✓
	Shallow laterolog resistivity (LLS)	✓	✓	✓	✓	✓	✓
	Microspherically focused log (MSFL)	✓	✓	✓	✓	✓	✓
	Photoelectric effect log (PEF)	✓	×	×	✓	✓	×
Core tests	Porosity	✓	✓	✓	✓	✓	×
	Permeability	✓	✓	✓	✓	✓	×

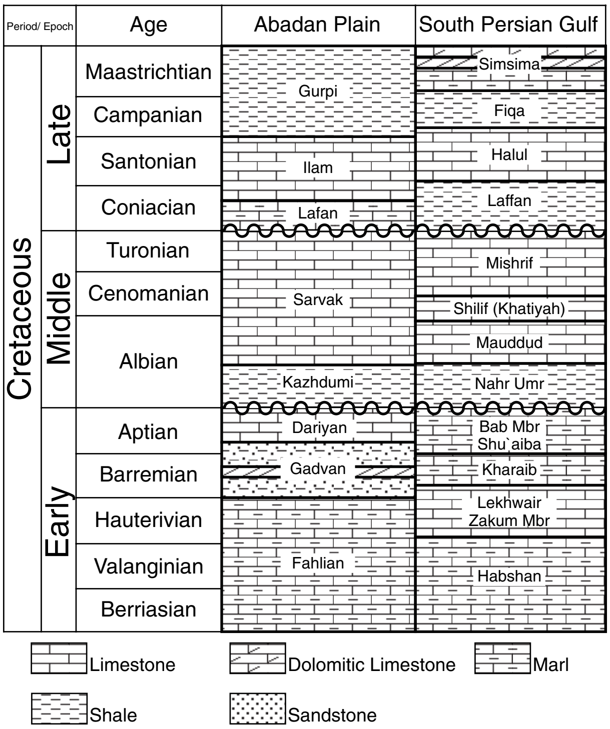


Figure 2. Comparison of stratigraphy of Cretaceous in Abadan Plain (SW Iran) and South Persian Gulf (United Arab Emirates and Qatar). Modified after Bashari (2007a).

in comparison to older parts. While Sarvak is overlaid on the Kazhdumi Formation with a transitional contact, its upper boundary is an unconformity, interpreted as uplift (Ghabeishavi *et al* 2010).

3. Methods and dataset

The dataset of each well includes well log data, core tests and production test results. Due to the inconsistency of well logs, those logs which are available in all the wells are selected and the others are ignored. The whole dataset and utilized well logs are introduced in table 1.

In this research, productive zones of the Sarvak interval are determined five times by four different methodologies. The first one is a conventional net pay determination procedure, which utilizes cut-off values on petrophysical data. The second approach is based on the flow equation. The third method is a newly developed procedure, based on the concept of conditional probability (Bayes theory). And the last methodology is based on fuzzy theory.

3.1. Conventional net pay determination

Conventionally, net pays are determined by applying cut-off values on porosity, shale percentage and water saturation values. There are a few procedures to find the cut-off values of petrophysical data. For a comprehensive study about the conventional methodology, respected readers are referred to Worthington and Cosentino (2005), Jensen and Menke (2006) and Worthington (2010). Here, cut-off values provided by National Iranian Oil Company (NIOC) reports are used to Q8 determine net pay zones through the Sarvak interval. The output of this methodology is crisp, i.e. productive or non-productive.

3.2. Diffusivity equation

A newly published procedure to determine productive zones is based on the flow equation. In this method, the diffusivity equation is solved by the Ei-function solution, and then rearranged into the form of relation (1). The index of productivity in this relation is the ratio of the flow rate to the pressure differential, which can be easily achieved by reversing the left-hand side of relation (1). For a detailed study about this methodology, the respected readers are referred to Masoudi *et al* (2011).

$$\frac{\Delta p(r,t)}{Q_0} = 70.6\frac{\mu_0}{kh} \times in\left(948\frac{\varphi\mu_0 c_t r^2}{kt}\right), \qquad (1)$$

where $p(r, t)$ is the pressure at radius r from the well after t seconds in psi, t is the time (h), k is the permeability (mD), Q_0 is the flow rate (rb d^{-1}) and h is the pay zone thickness (ft). Using the Ei-function solution in solving the diffusivity equation incorporates approximation error. To keep this error less than 0.25% the input of logarithm should not exceed 0.01 (Ahmed 2001).

3.3. Bayesian classifier

Q9 This methodology is based on Bayes theory. The algorithm used here is a parametric Bayesian classifier, the discrimination function of which is introduced by Duda *et al* (2000).

- One of the wells which contains all the probable conditions is utilized as a training well to train the Bayesian classifier through it. The trained Bayesian classifier will be applied on all other wells too.
- Intervals of well tests are marked by the production rate: if the interval does not produce oil, net pay value (npv) is defined as 1, if the corresponding depth produces oil less than 1500 barrels per day, then the net pay value equals 2 and finally if that interval produces oil more than 1500 barrels per day, then the net pay value is assumed as 3 in the corresponding well test interval.
- Data of each mentioned class are divided into two parts: 70% for training Bayesian and 30% for testing the precision of trained Bayesian.
- Probability distribution function of each feature in any of the three classes is calculated by training data.
- For each test data (depth), the probability of belonging to each possible net pay value (npv = 1, 2 or 3) is calculated using equation (2):

$$P(\text{npv}) = \sum_{i=1}^{n} P(\text{npv}|d_i) \times P(d_i), \qquad (2)$$

  where npv stands for 'net pay value' and d_i represents the value of the ith feature out of total n features.
- The most probable net pay value (i.e. npv with the highest P(npv) value) is selected as the productivity index of corresponding depth, determined by the Bayesian classifier.

3.4. Fuzzy fusion

Sugeno integral is a famous nonlinear operator to fuse multisensory data. Fuzzy integrals have shown great results in fusing classifiers (Kuncheva 2004). The algorithm used here to apply Sugeno integral is presented below.

- Sort the components of the input vector ($\mathbf{x}$) from the highest to the lowest value i.e.

$$x = [x_1, x_2, \ldots, x_n] \rightarrow x_s = [x_{s_1}, x_{s_2}, \ldots, x_{s_n}]$$
$$\text{that}: x_{s_1} > x_{s_2} > \ldots > x_{s_n}.$$

- Arrange fuzzy densities of the components according to the sorted input vector ($\mathbf{x}_s$), i.e. $g_s = [g_{s_1}, g_{s_2}, \ldots, g_{s_n}]$.
- Calculate$\lambda > -1$ using relation (3):

$$\lambda + 1 = \prod_{t=1}^{n} (1 + \lambda g_{s_t}). \qquad (3)$$

- Set $g(1) = g_{s_1}$, and for $t = 2$ to n, $g(i)$ should be calculated recursively using equation 4):

$$g(t) = g_{s_t} + g(t-1) + \lambda g_{s_t} g(t-1). \qquad (4)$$

- Calculate the output of Sugeno integral using equation (5):

$$\mu(x) = ^{\max}_{t=1:n} \{\min\{x_{s_t}, g(t)\}\}. \qquad (5)$$

3.5. Performance assessment

Confusion matrix and classification correctness rate (CCR) are used to evaluate the correctness of each classifier. The confusion matrix shows how input vectors are classified. The element (i,j) is the number of vectors that are classified in the ith class while belonging to the jth real class (Theodoridis and Koutroumbas 2003). The CCR is the ratio of the summation of corrected classified elements (usually on the trace of the confusion matrix) to the number of classes.

4. Results

4.1. Output of the conventional procedure

By using the conventional method, productive zones are determined crisply (figure 3). Cut-offs used to classify pay zones from non-pays are extracted from NIOC reports. For well no 1, 3, 4, 5 and 6, horizons with porosity values higher than 5%, water saturation of less than 40% and shale volume percentage of less than 25% are considered as pay zones. However for well no 2, the cut-offs of porosity and water saturation are considered as 6% and 50%, respectively, while the cut-off of shale volume is the same as in other wells.

As shown in figure 3, the whole Sarvak interval is divided into five different zones. This classification is the result of visual assessment. The upper half of Sarvak is more productive than the lower half, and zone number 2 is the most productive zone. Well no 4 and 5 are not incorporated in this figure because of inconsistency of their classification with the other wells. This inconsistency is probably due to imprecise classification of the Sarvak interval by the conventional procedure because the CCR value of well no 4 is considerably low in comparison to the other wells (figure 7(a)).

4.2. Output of the diffusivity equation-based methodology

For applying this methodology, in the first place, porosity and permeability values are estimated by an MLP-structured ANN, and water saturation is calculated by the Archie equation (Johnson and Pile 2002). As it is described below equation (1), Q10
the distance from the well axis (r) and time (t) are considered as 5 ft and 5000 h respectively to keep the error of approximation less than 0.25%. Then, the index of productivity $\left(\frac{Q_0}{\Delta p(r,t)}\right)$

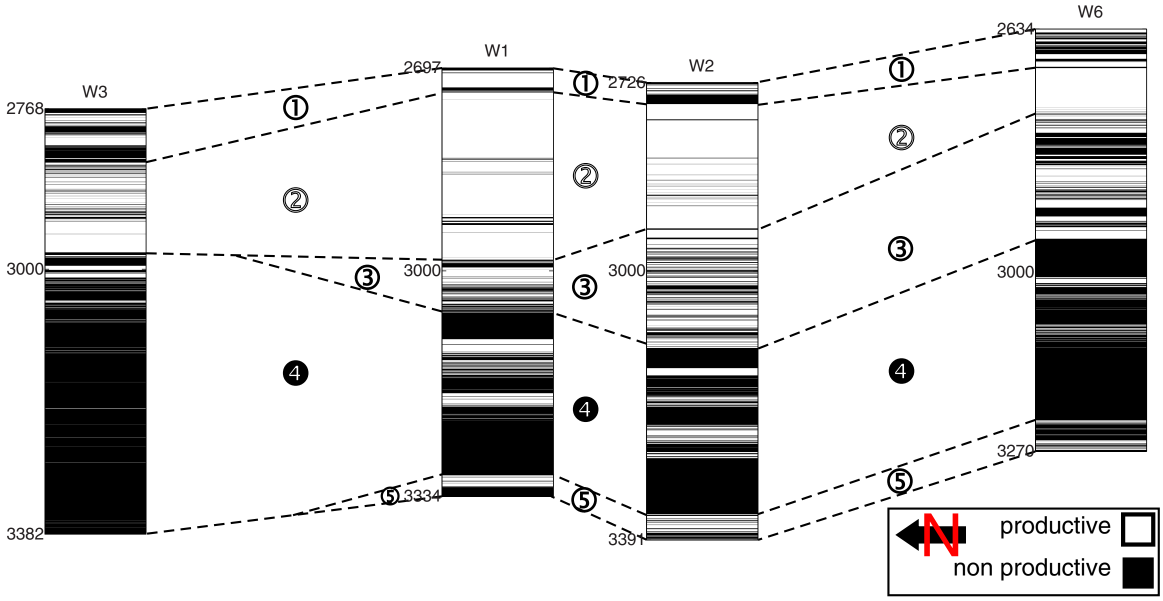


Figure 3. Output of the conventional procedure in distinguishing net pay zones of Sarvak formation.

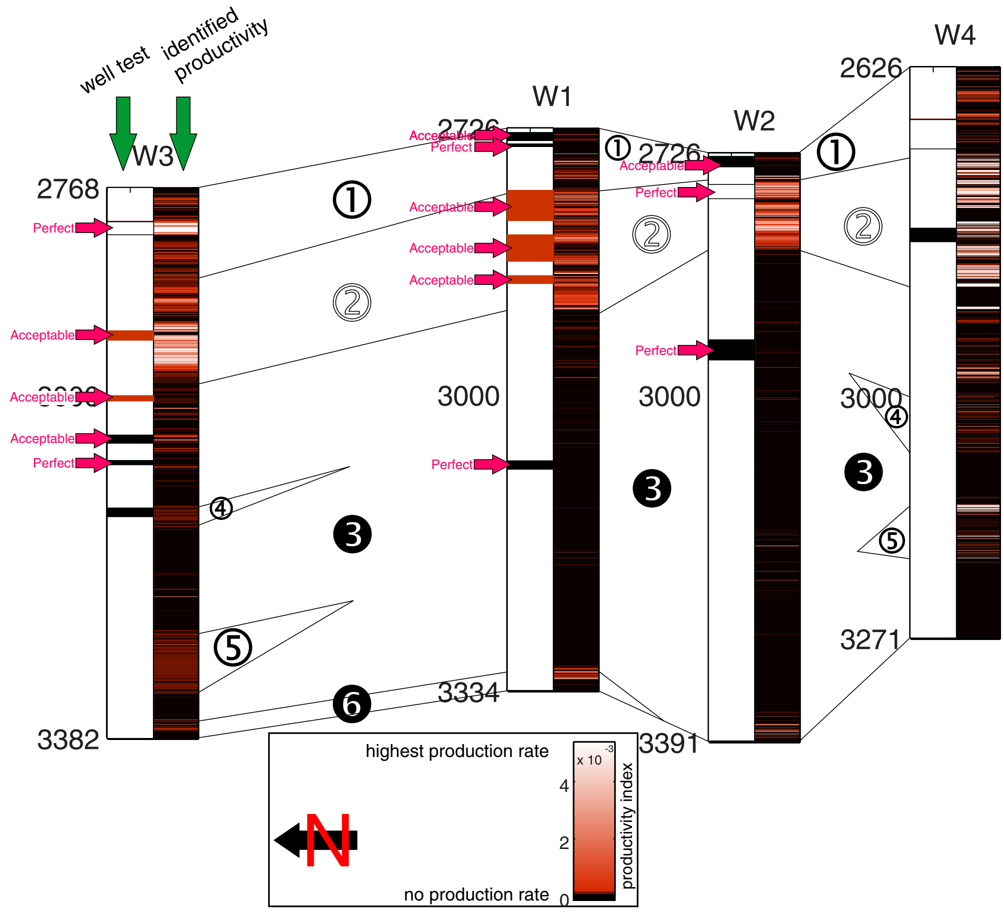
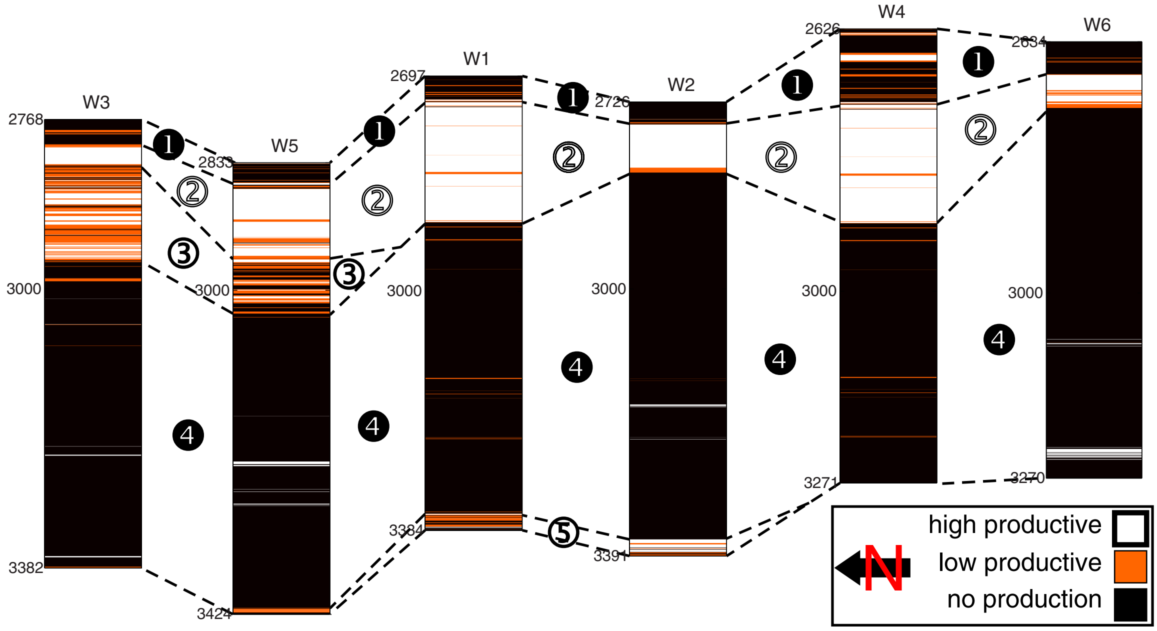


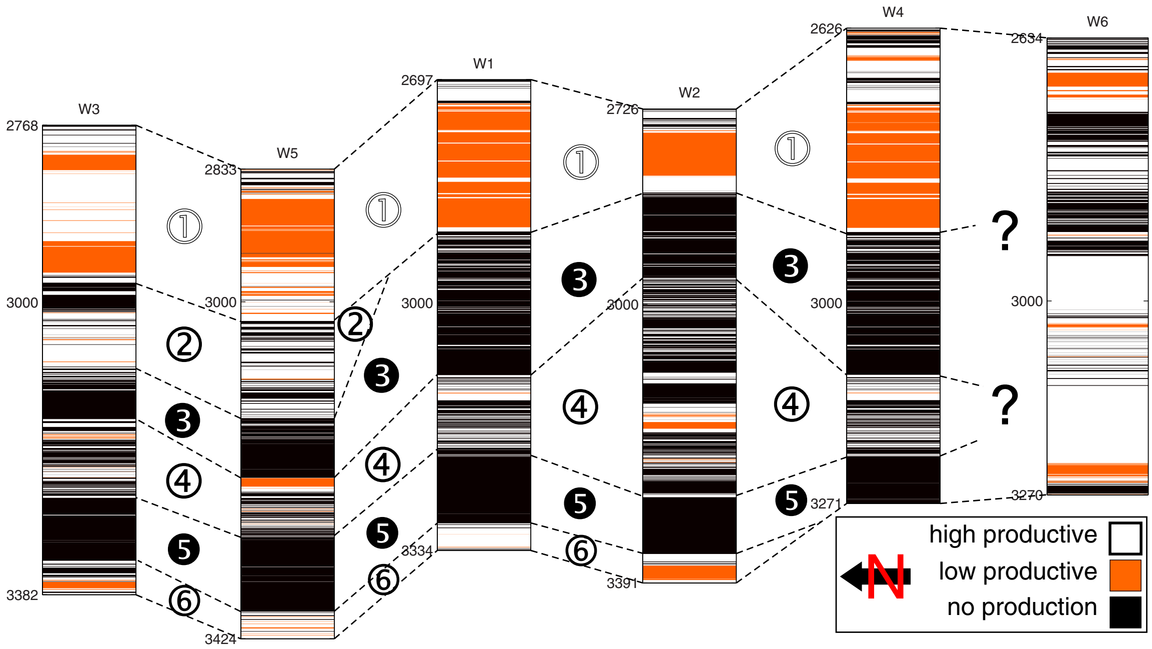
Figure 4. Output of the diffusivity-based methodology (index of productivity: $(\frac{Q_0}{\Delta p(r,t)})$) in determining the productive zones of Sarvak formation.

is calculated using equation (1), and presented in figures 6 and 4.

It was impossible to calculate the confusion matrix or CCR values for the outputs of this methodology because these performance assessment indices are compatible with discrete outputs, while the output of this methodology is continuous. To check the validity of the results, the outputs of well tests are presented in the figure next to the outputs of the methodology. It is observed that productivity identification is at least acceptable within 14 well test intervals out of total 16 well tests.



(*a*) Output of classifier Bayesian-3



(*b*) Output of classifier Bayesian-4

Figure 5. Outputs of Bayesian classifiers in determining the productive zones of Sarvak formation. White colour means npv = 3, orange means npv = 2 and black is npv = 1.

It was impossible to apply this methodology on well no 5 and 6 due to lack of core report, and consequently lack of porosity and permeability data. Generally, the upper part of Sarvak is more productive than the lower part, and zone number 2 has the highest productivity index.

4.3. Outputs of Bayesian classifiers

For training Bayesian classifiers using the mentioned algorithm, all the classes should exist in the training datasets. Therefore, datasets which can be used for training are well no 3 and 4 (see table 1). Furthermore in this research, Bayesian is trained twice by these two wells; one trained classifier is named Bayesian-3 (trained in well no 3), the other is called Bayesian-4 (trained in well no 4). The input well logs for training are LLD and LLD/LLS. Then, the trained classifiers are applied on all the wells to determine productive zones (figure 5).

As is obvious, the outputs of Bayesian-3 and 4 differ, to some extent, from each other (figures 5(*a*), (*b*)). Bayesian-3 identifies productive zones more pessimistically, whereas the output of Bayesian-4 is more optimistic. In this figure, like the outputs of previous methodologies, the upper half of

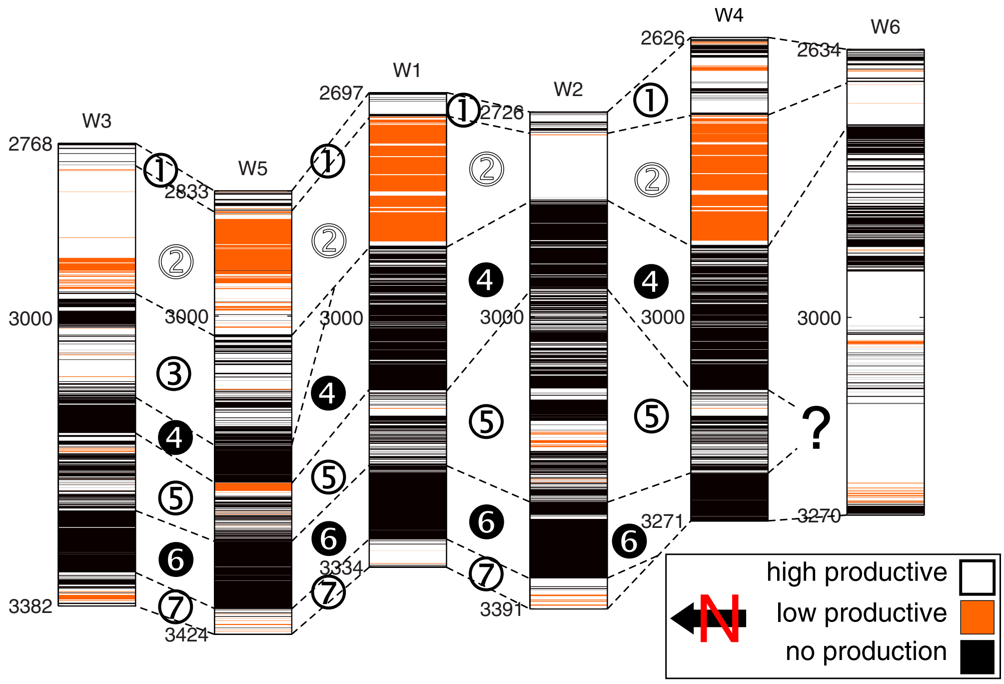
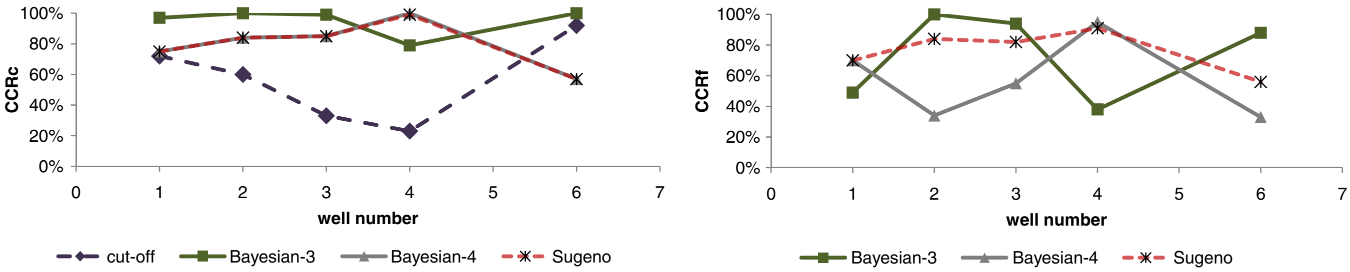


Figure 6. Output of Sugeno integral (fusing Bayesian-3 and 4) in determining the productive zones of Sarvak formation. White colour means npv = 3, orange means npv = 2 and black is npv = 1.



(*a*) Crisp CCR values (CCRc)

(*b*) Fuzzy CCR values (CCRf)

Figure 7. CCR of each methodology (conventional, Bayesian and fuzzy-based) in well no 1, 2, 3, 4 and 6. It was impossible to calculate the CCR in well no 5 due to lack of a valid well test. CCR values are calculated in two states: crisp and fuzzy.

Sarvak is more productive than the lower part. In the output of Bayesian-3 (figure 5(*a*)), zone number 2 is the most productive one, and in the output of Bayesian-4 (figure 5(*b*)), zone number 1 (equivalent of zone number 2 in Bayesian-3) is the most productive among the other zones. Bayesian-4 is unable to predict the productive zones through well no 6 precisely. It can be inferred from the low CCR value (figure 7), and the inconsistency of its output with other wells (figure 5(*b*)). The most significant difference between the outputs of Bayesian-3 and 4 is a weak productive zone identified by Bayeisan-4 (zone 4 in figures 5 and 6(*b*)), while Bayesian-3 has not determined this zone. In the next part, the outputs of Bayesian-3 and 4 are fused, by a fuzzy operator, Sugeno integral, to reach a more reliable result.

4.4. Output of fuzzy fusion

The outputs of Bayesian-3 and 4 are integrated by Sugeno operator to generate a new zoning. This zoning is more similar to the output of Bayesian-4 rather than that of Bayesian-3. In this case, it seems that Sugeno integral has fused Bayesian classifiers optimistically. Incorrect classification of well no 6 is the worst disadvantage of this fusion-based zoning. However, higher certainty of this zoning in comparison to Bayesian-based zonings is the biggest advantage of this fuzzy-based zoning. The zoning is carried out by the means of visual evaluation, which is illustrated in figure 6.

5. Final integrated model for the productivity of the Sarvak formation

Based on the introduced methodologies, five zoning models for the productivity of the Sarvak reservoir are generated (figures 3–6). The differences, which exist between these figures, raise a considerable uncertainty in identifying productive zones of this reservoir rock. To solve this problem, these zonings are integrated by the technique of majority voting. In this integration, CCR values, calculated for each methodology, are used (figure 7). Based on CCRc values (figure 7(*a*)), the outputs of both Bayesian classifiers and

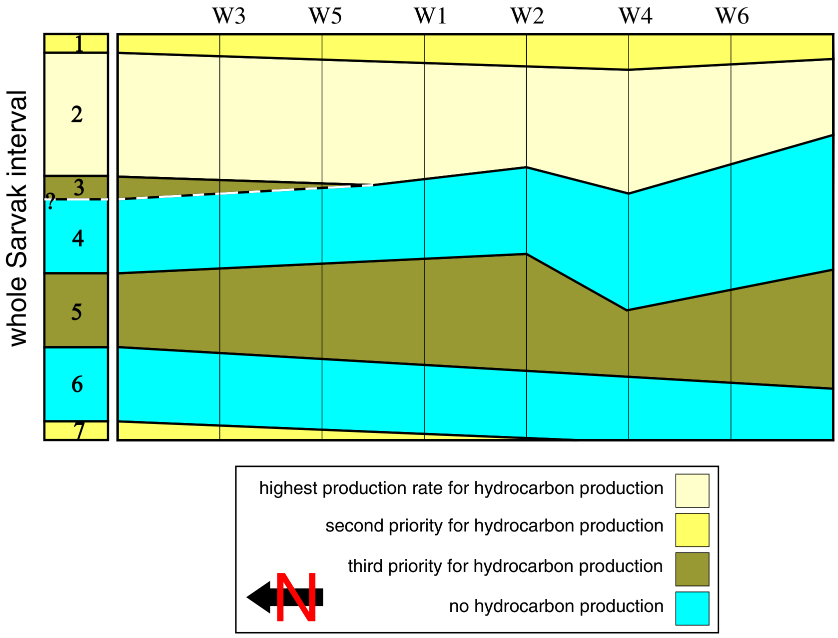


Figure 8. Final zoning for the productivity of Sarvak formation, resulted from integrating the outputs of different classification methods.

Sugeno integral are precise. However, due to CCRf values (figure 7(*b*)), the average of precision in Sugeno integral is not only the highest but also more constant well to well.

In the final zoning (integrating the five mentioned classifications), Sarvak formation is generally divided into two major parts: productive interval, which is approximately shallower than 3000 m (zones 1 to 3), and non-productive interval, which is almost deeper than 3000 m (zones 4 to 7). In a finer identification, this reservoir rock is divided into seven different classes (figure 8) from zone 1 to 7, in a descending order. Zone number 2 has the highest production rate, which makes it the most suitable horizon for perforation. Zones 1 and 7 are in the second priority and zone numbers 3 and 5 are in the third priority for production. Finally, zones 4 and 6 are not classified as oil producing zones. These horizons produce water instead.

6. Discussion

In this part, the final zoning is compared to previous sedimentological facts to check the validity of the proposed zoning. Sarvak is deposited in three different depositional environments. Upper Sarvak belongs to fore reef with good reservoir quality; middle part belongs to main reef, which has the best reservoir quality, consequently very good productivity; and bottom Sarvak is a back reefal facies, related to low-energy environment with bad reservoir quality (Bashari 2007a). This sequence is comparable to the final results of this work too. Zone 1 with good reservoir quality is probably representative of fore reef deposition; zone 2 with the highest production rate is most likely related to the main reef with the best reservoir quality, and the productivity of other zones is similar to back reef i.e. bad reservoir quality. So, the proposed model is compatible with geological facts.

There are two zones which do not have lateral continuity in the southern part of the field (zones 3 and 7 in figure 8). It should be noted that these zones are not sedimentary zones; in fact, they are productive zones, which represent the production rate of that interval. This lateral variation may be due to different depositional environment or diagenetic processes. By the way, the effect of diagenetic processes is more probable because of two reasons: the first reason is that the variation in depositional environment rarely occurs within the field scale; on the other hand Sarvak has been under various diagenetic events such as dissolution, dolomitization, etc, affecting the porosity and permeability of the reservoir, consequently the rate of liquid production of the rock (Bashari 2007c, Taghavi *et al* 2007, Zamani *et al* 2010).

7. Conclusions

The conclusions of this paper can be categorized into two parts: methodological and geological. Methodological conclusions are the advantages and disadvantages of the introduced methodologies in identifying productive zones. Geological conclusions are those scientific facts and interpretations, inferred about the Sarvak reservoir in the field under study. The compatibility of the final method with geological facts, presented under discussion is the most valuable advantage of this work that verifies the application of the proposed methods in determining productive zones of Sarvak reservoir in this field.

Methodological conclusions. All the four newly developed methodologies identify productive zones more precisely than the conventional procedure. Besides, these proposed methods are capable of determining the productive zones fuzzily, while the conventional procedure classifies pay zones crisply. Due to CCRf values, Sugeno integral is the most precise fuzzy classifier among all the methodologies. In addition, the generalization ability of Sugeno operator is higher than that of other methodologies due to more constant CCRf values in different wells. At last, the continuous output of the diffusivity equation-based method is its obvious advantage among others.

Geological conclusions. On a large scale, Sarvak formation is divided into two major parts: productive interval, which is shallower than about 3000 m, and non-productive interval, which is approximately deeper than 3000 m. However on a finer scale, this reservoir rock is classified into seven zones and that zone number 2 has the highest production rate. In addition, the lateral variations of productive zones (3 and 7) are probably due to diagenetic processes, which happened on this giant reservoir.

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