Using a Modified GOI Index (Effective Grid Containing Oil Inclusions) to Indicate Oil Zones in Carbonate Reservoirs

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Abstract: The GOI (grains containing oil inclusions) index is used to distinguish oil zones, oil-water zones and water zones in sandstone oil reservoirs. However, this method cannot be directly applied to carbonate rocks that may not have clear granular textures. In this paper we propose the Effective Grid Containing Oil Inclusions (EGOI) method for carbonate reservoirs. A microscopic view under 10× ocular and 10× objective is divided into 10×10 grids, each with an area of 0.0625 mm×0.0625 mm. An effective grid is defined as one that is cut (touched) by a stylolite, a healed fracture, a vein, or a pore-filling material. EGOI is defined as the number of effective grids containing oil inclusions divided by the total number of effective grids multiplied by 100%. Based on data from the Tarim Basin, the EGOI values indicative of the paleo-oil zones, oil-water zones, and water zones are >5%, 1%–5%, and <1%, respectively. However, the oil zones in young reservoirs (charged in the Himalayan) generally have lower EGOI values, typically 3%–5%.

Key words: GOI, EGOI, ancient oil reservoirs, late accumulation, carbonate reservoirs

1 Introduction

“GOI” is the ratio of the number of grains in a sample that contain oil inclusions within them to the total number of grains in the sample (Eadington et al., 1996). Based on studies of sandstone reservoirs in Australia, it was proposed that GOI values can be used to evaluate the degree of oil saturation in reservoirs (O'Brien et al., 1996; Eadington et al., 1996; Lisk et al., 2002; George et al., 2004a, 2004b), and the method has been applied to assess paleo-oil reservoirs in terms of oil-water interface and charging history (George et al., 2004a, 2004b; Wang et al., 2004; Jiang et al., 2006). The concept was also used to distinguish palo-reservoirs, migration pathways and aquifers, with GOI values of ≥5%, 1%–5% and ≤1%, respectively (Eadington et al., 1996; George et al., 2004a, 2004b; Wang et al., 2004; Jiang et al., 2006).

The GOI method has been applied to many sandstone oil-gas reservoirs in China, including the Paleogene-Neogene sandstone reservoirs in the Qaidam Basin (Zhang et al., 2009b; Li et al., 2009, 2011; Yang et al., 2009), Jurassic and Cretaceous sandstone reservoirs in the Junggar Basin (Xie et al., 2007), Silurian, Carboniferous, Jurassic, and Cretaceous sandstone reservoirs in the Tarim Basin (Zhang et al., 2000; Wang et al., 2004, 2006; Jiang et al., 2006), Cretaceous sandstone reservoirs in the northern part of the Songliao Basin (Jiang et al., 2006), Paleogene sand lentoid reservoirs in the Jiayang Depression (Hao et al., 2006; Song, 2007; Zhuo et al., 2011), and Upper Paleozoic sandstone reservoirs in the Ordos Basin (Li et al., 2012; Chen et al., 2013). It was found that the GOI indexes established in Australia are applicable in many sandstone reservoirs in China (e.g., Wang et al., 2005), although GOI values lower than the Australian “standards” were also found, which may be related to rapid, late or shallow accumulations, and it was cautioned that the “standard” GOI criteria should be evaluated case by case (Cao et al., 2011).

However, the application of the GOI method to carbonate rocks is not straightforward. Unlike sandstones that consist of recognizable grains, carbonate rocks may be comprised of various components which may not be easily described as grains, such as micrite, crystalline
carbonates, and biologically bonded fabrics. Thus, the traditional GOI method, which requires the counting of grains, cannot be used for most carbonate rocks. In this paper, we introduce a modified GOI index, called effective grid containing oil inclusions (EGOI), and apply it to the studies of carbonate reservoirs in the Tarim Basin. The EGOI results are compared with those of quantitative grain fluorescence (QGF) (Liu and Eadington, 2005; Li et al., 2006), and their significance for oil charging history is discussed.

2 The Effective Grid Containing Oil Inclusions (EGOI) Method

Oil inclusions in carbonate rocks are commonly found along stylolites (Figs. 1a, 1i), healed fractures (Figs. 1b, 1l), veins (Figs. 1c, 1e-1h, 1k), and pore-filling materials (Figs. 1d, 1j). The oil inclusions are easily recognizable with a fluorescence microscopy (Fig. 1).

A 10×10 grid, covering an area of 0.625 mm×0.625 mm, was designed for petrographic observation of thin sections under 10× oculars and a 10× objective (Fig. 2). The grids that contain stylolites, healed fractures, veins, or pore-filling materials are called “effective grids”, and the effective grids that contain oil inclusions are called “effective grids containing oil inclusions”. The EGOI index is defined as the ratio of effective grids containing oil inclusions to the total effective grids multiplied by 100%. For example, in Fig. 2a there are 10 grids that are cut through by the healed fracture, so the number of effective grids is 10, and there are 2 effective grids that contain oil inclusions, so the EGOI index = 2/10 × 100% = 20%. In Fig. 2b, the stylolite traverses 20 grids, and there are 4 grids that are touched (partly) by oil inclusions, so the EGOI index = 4/20 × 100% = 20%. Similarly, the EGOI index for Fig. 2c and Fig. 2d are calculated to be 13.15%, and 3.12%, respectively.

For crystalline carbonates, the EGOI index is defined as the ratio of the number of crystals containing oil inclusions to the total number of crystals with the 10×10 grid. This is similar to the conventional GOI method, although “crystals” rather than “grains” are counted.

Fig. 1. Photomicrographs showing occurrences of oil inclusions in Cambrian - Ordovician carbonate reservoirs in the Tarim Basin. (a), Yellow fluorescent hydrocarbon fluid inclusions distributed along a stylolite, well Ha 6-1, Ordovician strata, 6665.30 m, fluorescence under ultraviolet excitation; (b), Blue fluorescent hydrocarbon fluid inclusion in healed fractures, well Badong 2, Ordovician strata, 4300.71 m, fluorescence under ultraviolet excitation; (c), Tawny fluorescent fluid inclusions in a calcite vein, well Tachong 62, Ordovician strata, 4753.83 m, fluorescence under ultraviolet excitation; (d), Blue fluorescent fluid inclusions in a pore-filling cement, well Jinyue 2, Ordovician strata, 7087.33 m, transmitted light + fluorescence under ultraviolet excitation; (e), Two stages of calcite veins, well Lungu 36, Ordovician strata, 5934.02 m, transmitted light + fluorescence under ultraviolet excitation; (f), as view as (e), fluorescence under ultraviolet excitation; (g), Blue fluorescent hydrocarbon fluid inclusions in a calcite vein, well Lungu26, Ordovician strata, 6090.54 m, fluorescence under ultraviolet excitation; (h), Yellow fluorescent hydrocarbon fluid inclusions, well Lungu 36, Ordovician strata, 6027.89 m, fluorescence under ultraviolet excitation; (i), Stage I hydrocarbon fluid inclusions distributed along a stylolite, well Qiga 1, Ordovician strata, 6682.81 m, transmitted light; (j), Tawny fluorescent hydrocarbon fluid inclusions in stage I, well Qiga 1, Ordovician strata, 6682.81 m, fluorescence under ultraviolet excitation; (k), Blue-white fluorescent fractures, well Qiga 1, 6689.75 m, Ordovician strata, fluorescence under ultraviolet excitation; (l), Blue fluorescent hydrocarbon fluid inclusions in healed fractures, well Yingmai 101, Ordovician strata, 5469.67 m, fluorescence under ultraviolet excitation.
3 Application to the Tarim Basin

3.1 Samples and methods

The Tarim Basin is a large superimposed compound Paleozi–Cenozoic sedimentary basin developed on pre-Sinian metamorphic basement (Jia, 1999). Large amount of carbonate such as dolomite and limestone were deposited during Early-Paleozoic in it (Feng et al., 2006, 2007; Chen et al., 2013b). More than half of the hydrocarbon resources in the basin are hosted in carbonate reservoirs (Huang, 2000), which are distributed in the Tabei, Tazhong, Tadong, and Bachu areas (Chen and Xu, 1994; Gu et al., 1999; Kang, 1999, 2002; Wu et al., 2002; Su et al., 2003; Song et al., 2004).

A total of 2749 thin sections from carbonate reservoirs from 19 wells in Tabei, Tazhong, Tadong, and Bachu were examined over many years (Zhang et al., 2009a, 2010, 2011, 2013). Of these, 649 thin sections contain oil inclusions, accounting for 30.7% of the total (Table 1). Oil inclusions show various fluorescence colors ranging from blue to yellow (Fig. 1). The strata are Cambrian to Ordovician, and the depths are from 4200 to 7100 m. Data from four wells (Yaha 7X-1, Lungu 36, Qigui 1, and Yingmai 101) are described in more detail than other wells in this study.

The thin sections were studied for EGOI and QGF at the Key Laboratory of Basin Structure & Hydrocarbon Accumulation of PetroChina. The EGOI analysis was conducted on doubly polished sections (0.5 mm thick) with an Axioskop 40A multi-functional fluorescence microscope, using the method described above. The QGF analysis was carried out for 120-mesh washed particles with a Varian Cary-Eclipse fluorescence analysis instrument, and the experimental condition was QGF-Carbonates (Ex: 228 nm, Em: 295–605 nm). A QGF value of less than 4 was used to indicate the water zone as opposed to the oil zone (Liu and Eadington, 2003, 2005; Jiang et al., 2006a; Chen et al., 2007).

3.2 Results

EGOI values were obtained from 19 wells in the Tarim Basin. The results are summarized in Table 2, and illustrated in Figs. 3–7. QGF values were measured for three wells (Yaha 7X-1, Lungu 36, and Yingmai 101) and compared with EGOI data (Figs. 3–5).

The Yaha 7X-1 well is a preparatory reconnaissance borehole located at the #7 fault structure zone at Yaha in the Tabei area. The samples were collected from Cambrian strata and are mainly composed of micritic limestone, micritic dolomite, and fine-grained dolomite. For the interval from 5810 to 5870 m, the QGF values are >6 (Fig. 3), suggesting that it was a paleo-oil reservoir. Most of the EGOI values in this interval are more than 5%, even up to 60% (Fig. 3). In contrast, samples deeper than 5880 m have QGF values <6, and EGOI values close to 0 (Fig. 3), suggesting that this interval was an oil-bearing water zone.

The Lungu 36 well is an exploratory well located at the east slope of the Tabei uplift. Two different kinds of oil inclusions, with yellow fluorescence and blue fluorescence, were observed in Ordovician limestones. The blue fluorescent oil inclusions appear to postdate the yellow fluorescent ones (Figs. 1e, 1f). These two types of oil inclusions were found in cores of 5930–5950 m (Figs. 1e, 1f) and 6016–6050 m (Figs. 1g, 1h). For the 5930–5950 m interval, EGOI values for both types of oil inclusions are >5%, and QGF values are >6 (Fig. 4), suggesting that this was in an oil zone when the oil inclusions were entrapped (Fig. 7 point d; Table 2 No. 19). In fact, this interval is still a commercial oil reservoir at present. For the cores from 6016–6050 m, both types of oil inclusions were only found in the 6016–6025 m interval, where EGOI values are >5% and QGF values are >4, whereas in the interval of 6025–6050 m, only yellow fluorescent oil inclusions (with EGOI index >5% and QGF >4) were found, and no blue fluorescent oil inclusions were discovered (Fig. 4).

The Yingmai 101 well is located in the Yingmaili area of the Tarim Basin. The majority of samples from this well do not contain oil inclusions, except for the 5450–5470 m interval, where blue fluorescent oil inclusions were observed, EGOI is 4%, and QGF is >4 (Fig. 5; Fig. 7 point a; Table 2 No. 10).

In samples from the Qigui well, dark brown oil inclusions with tawny fluorescent color were observed along stylolites (Fig. 1i), postdated by fractures with blue-white fluorescence (Fig. 1k). Most of the EGOI values of the oil zone in the Qigui 1 well range from 3% to 5% (Fig. 6; Fig. 7 point c; Table 2 No. 18).

Overall, the EGOI values from the Tarim Basin range from 0% to 100% (Table 2; Figs. 6–7). The intervals

Table 1 The statistics of hydrocarbon inclusions in thin sections from carbonate reservoirs in the Tarim Basin

<table>
<thead>
<tr>
<th>Area</th>
<th>Number of thin sections</th>
<th>Number of thin sections with oil inclusions</th>
<th>Number of thin sections with EGOI value</th>
<th>Percentage of thin sections with oil inclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tabei Uplift</td>
<td>1755</td>
<td>649</td>
<td>649</td>
<td>37.0</td>
</tr>
<tr>
<td>Tazhong Uplift</td>
<td>515</td>
<td>128</td>
<td>128</td>
<td>24.9</td>
</tr>
<tr>
<td>Bachu Uplift</td>
<td>320</td>
<td>28</td>
<td>28</td>
<td>8.8</td>
</tr>
<tr>
<td>Tadong Uplift</td>
<td>150</td>
<td>36</td>
<td>36</td>
<td>24.0</td>
</tr>
<tr>
<td>Total</td>
<td>2740</td>
<td>841</td>
<td>841</td>
<td>30.7</td>
</tr>
</tbody>
</table>
Fig. 2. Sketches showing the method of calculating the EGOI values in carbonate rocks in a 10×10 grid under 10× ocular and 10× objective.

(a) Healed fracture: the total number of effective grids is 10, and the number of effective grids containing oil inclusions is 2, so the EGOI is 2/10 = 20%; (b) Stylolite: the total number of effective grids is 20, and the number of effective grids containing oil inclusions is 4, so the EGOI is 4/20 = 20%; (c) Vein: the total number of effective grids is 38, and the number of effective grids containing oil inclusions is 5, so the EGOI is 5/38 = 13.15%; (d) Pore-filling material: the total number of effective grids is 32, and the number of effective grids containing oil inclusions is 1, so the EGOI is 1/32 = 3.12%.

Fig. 3. EGOI and QGF index profiles of the the Yaha 7X-1 well.
Table 2 EGOI values of oil and water zones in carbonate reservoirs in the Tarim Basin

<table>
<thead>
<tr>
<th>Number</th>
<th>Well</th>
<th>Depth range (m)</th>
<th>Formation</th>
<th>Hydrocarbon shows</th>
<th>EGOI (%) Min</th>
<th>Max</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>He 3</td>
<td>4020.54-4039.51</td>
<td>O</td>
<td>oil zone</td>
<td>20</td>
<td>22</td>
<td>21.60</td>
</tr>
<tr>
<td>2</td>
<td>Baong 2</td>
<td>4190.02-4309.26</td>
<td>O</td>
<td>oil zone</td>
<td>5</td>
<td>70</td>
<td>28.50</td>
</tr>
<tr>
<td>3</td>
<td>Zhonggu 17-1H</td>
<td>6077.56-6083.61</td>
<td>O</td>
<td>water zone</td>
<td>0</td>
<td>6</td>
<td>0.93</td>
</tr>
<tr>
<td>4</td>
<td>Tarhong 201-1H</td>
<td>5959.66-5460.87</td>
<td>O</td>
<td>oil zone</td>
<td>1</td>
<td>13</td>
<td>7.37</td>
</tr>
<tr>
<td>5</td>
<td>Tarhong 721-81H</td>
<td>4942.56-4953.62</td>
<td>O</td>
<td>water zone</td>
<td>0</td>
<td>0.85</td>
<td>0.28</td>
</tr>
<tr>
<td>6</td>
<td>Tarhong 721-81H</td>
<td>4945.88-4951.52</td>
<td>O</td>
<td>oil zone</td>
<td>5.5</td>
<td>22.3</td>
<td>6.50</td>
</tr>
<tr>
<td>7</td>
<td>Yingmai 2</td>
<td>5340.03-6050.31</td>
<td>O</td>
<td>oil zone</td>
<td>4</td>
<td>100</td>
<td>73.80</td>
</tr>
<tr>
<td>8</td>
<td>Yingmai 2</td>
<td>6197.50-6200.12</td>
<td>O</td>
<td>oil zone</td>
<td>1.5</td>
<td>4</td>
<td>2.75</td>
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<tr>
<td>9</td>
<td>Yingmai 2</td>
<td>6054.45-6058.40</td>
<td>O</td>
<td>oil zone</td>
<td>5</td>
<td>65</td>
<td>41.25</td>
</tr>
<tr>
<td>10</td>
<td>Yingmai 201</td>
<td>5869.35-6086.05</td>
<td>O</td>
<td>oil zone</td>
<td>4</td>
<td>100</td>
<td>39.00</td>
</tr>
<tr>
<td>11</td>
<td>Yingmai 201</td>
<td>5878.33-6199.80</td>
<td>O</td>
<td>water zone</td>
<td>0</td>
<td>3</td>
<td>0.38</td>
</tr>
<tr>
<td>12</td>
<td>Yingmai 202</td>
<td>5874.76-6061.10</td>
<td>O</td>
<td>oil zone</td>
<td>10.1</td>
<td>14</td>
<td>12.65</td>
</tr>
<tr>
<td>13</td>
<td>Yingmai 202</td>
<td>5865.80-6015.30</td>
<td>O</td>
<td>poor oil zone</td>
<td>1</td>
<td>3</td>
<td>2.30</td>
</tr>
<tr>
<td>14</td>
<td>Yingmai 101</td>
<td>5469.67</td>
<td>O</td>
<td>water zone</td>
<td>4</td>
<td>4</td>
<td>4.00</td>
</tr>
<tr>
<td>15</td>
<td>Yingmai 101</td>
<td>7099.52-7094.05</td>
<td>O</td>
<td>oil zone</td>
<td>3</td>
<td>60</td>
<td>35.25</td>
</tr>
<tr>
<td>16</td>
<td>Yingmai 101</td>
<td>6915.68-6923.31</td>
<td>O</td>
<td>oil zone</td>
<td>4</td>
<td>100</td>
<td>31.25</td>
</tr>
<tr>
<td>17</td>
<td>Xinken 7</td>
<td>6835.82-6842.20</td>
<td>O</td>
<td>oil zone</td>
<td>2</td>
<td>85</td>
<td>22.83</td>
</tr>
<tr>
<td>18</td>
<td>Xinken 7</td>
<td>6731.15-6737.55</td>
<td>O</td>
<td>poor oil zone</td>
<td>1</td>
<td>35</td>
<td>12.67</td>
</tr>
<tr>
<td>19</td>
<td>Xinken 7</td>
<td>6625.43-7047.00</td>
<td>O</td>
<td>water zone</td>
<td>0</td>
<td>3</td>
<td>0.51</td>
</tr>
<tr>
<td>20</td>
<td>Xinken 7</td>
<td>6639.36-6641.00</td>
<td>O</td>
<td>oil zone</td>
<td>35</td>
<td>45</td>
<td>41.67</td>
</tr>
</tbody>
</table>

Fig. 4. EGOI and QGF index profiles of the Lungu 36 well.

Considered to be oil zones generally have EGOI values >5%, and poor oil zones have EGOI of 1%~5%, whereas water zones are characterized by EGOI values <1% (Figs. 6~7). The poor oil zones refer to reservoirs which have lower resistivity, lower permeability and lower oil saturation than conventional oil zones.

4 Discussions

Based on the data from the Tarim Basin, we propose that the EGOI criteria for distinguishing paleo-oil zones, oil-water zones, and dry or water zones in carbonate reservoirs are similar to those of conventional GOI for
sandstone reservoirs, i.e., EGOI ≥5% for paleo-oil zones, EGOI = 1%–5% for oil-water zones, and EGOI ≤1% for water zones. However, there are noticeable exceptions, which can be related to the evolution and charging history of the reservoirs, as discussed below.

If an oil reservoir has not significantly changed since it was charged, samples from modern oil reservoirs will likely have EGOI >5%, as is the case for most oil reservoirs in the Tarim Basin. However, in some cases, EGOI values >5% have been found in some present-day water zones, such as the 6016–6025 m interval in the Lungu 36 well (Fig. 7 point d). This suggests that this interval used to be an ancient oil zone, which was later displaced by water. Similarly, the high EGOI (>12.6) in the poor oil zone in well Ha 801 (Fig. 7 point b; Table 2 No. 14), also suggest that this interval was once an oil-saturated zone. In contrast, samples from the water zone of the Tazhong 721-8H, Tazhong 17-1H, Yingmai 202 and Ha 6 wells have EGOI values mostly ≤1%, indicating that these intervals have been always filled with water.

Some oil reservoirs have EGOI values <5%, such as the Qigu 1 well (Fig. 7 point c; Table 2 No. 18) and the Yingmai 101 well (Fig. 7 point a; Table 2 No. 10). The low EGOI values (3%–5%) for the Qigu 1 well in the Tabei area are related to the late (mainly in Himalayan) charging and limited time for oil inclusion entrapment, although an earlier phase of oil charging was also recorded. The low EGOI values for the Yingmai 101 well
Fig. 6. EGOI values of oil and water zones in carbonate reservoirs in the Tarim Basin.

Fig. 7. Average EGOI values from 19 wells in Tarim Basin (well numbers correspond to those in Table 2).
Point a is from well Yingma1 101, water zone (paleo-oil zone); point b is from well Ha 801, poor oil zone; point c is from well Qigao 1, oil zone; point d is from well Lunga 36, water zone (paleo-oil zone).

may also be caused by late oil-gas recharging.

5 Conclusions

(1) The conventional GOI method is mainly used for sandstone reservoirs, and cannot be readily applied to carbonate reservoirs. A modified GOI index, called the effective grid containing oil inclusions (EGOI), is proposed for the latter.

(2) Using a 0.625 mm×0.625 mm grid under 10× ocular and 10× objective, an effective grid is defined as one that is cut (touched) by a stylolite, a healed fracture, a vein, or a pore-filling material. EGOI is defined as the ratio of the number of effective grids containing oil inclusions to the total number of effective grids multiplied by 100%.

(3) Application of the EGOI method to the Tarim Basin suggests that paleo-oil zones are characterized by EGOI values >5%, oil-water zones by EGOI values of 1%–5%, and water zones by EGOI values <1%.

(4) EGOI values ≥5% may be found in present-day water zones. These intervals were likely paleo-oil zones, and were displaced by water during the evolution of the reservoirs.

(5) For oil reservoirs that were charged late (Himalayan), EGOI values are relatively low (typically 3%–5%), probably due to limited time for oil inclusion entrapment.

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