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Research Article

Study on Pulse Characteristic of Produced Crude Composition in CO_2 Flooding Pilot Test

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It has been observed in many laboratory tests that the carbon number of the maximum concentration components (CNMCC) of produced oil varies monotonically with CO_2 injection volume at the core scale. However, in CO_2 flooding pilot test at the field scale, we find that the CNMCC is usually nonmonotonic function of CO_2 injection volume, which is called "pulse characteristic" of CNMCC. To investigate the mechanism of this phenomenon, we analyze the physical process of CO_2 flooding in heterogeneous reservoir and explain the reason of the pulse characteristic of CNMCC. Moreover, two 3D reservoir models with 35 nonaqueous components are proposed for numerical simulation to validate the conjecture. The simulation results show that pulse characteristic of CNMCC only occurs in the heterogeneous model, confirming that the pulse characteristic results from the channeling path between wells, which yields nonmonotonic variation of oil-CO_2 mixing degree. Based on it, a new method can be developed to identify and quantify the reservoir heterogeneity.

1. Introduction

In recent years, the gas drive technology has been rapidly developed and widely applied. It has become another important way to improve oil recovery, besides thermal recovery and chemical flooding [1, 2]. CO_2 has several advantages on enhancing oil recovery, such as being easily soluble in oil, reducing oil viscosity [3], and reducing residual oil saturation [4]. Therefore, CO_2 drive is widely used in different types of oilfield, including sand and carbonate reservoirs [5–8].

The process of CO_2 displacement differentiates different components in oil [9]. This differentiation results in different flow rates among the compositions with different viscosities: light compositions are quickly carried away by CO_2, while heavy compositions move significantly slower. Consequently, produced oil composition will change along with the increase of displacement time.

It is widely known that the carbon number of maximum concentration components (CNMCC) increases monotonically with CO_2 injection volume, which has been confirmed by the experimental results [10, 11]. In 2011, Yang et al. [10] analyzed the produced oil components in a CO_2 slime tube tests under conditions of immiscible and miscible flooding, respectively. The chromatograph analysis results of the two tests both show that the CNMCC of the produced oil increases monotonically with CO_2 injection volume. In 2015, Zhou et al. [11] analyzed the contents of the fluid compositions under different pressures by an 18-meter slime tube made of quartz. The results show that, at 18.1 MPa, the CNMCC of produced oil increases from C9 to C14 monotonically and gradually with the increase of CO_2 injection volume. At 25.2 MPa, the CNMCC of produced oil increases from C10 to C20 monotonically and quickly with the increase of CO_2 injection volume.

Despite several laboratory studies on CNMCC variation at core scale, the researchers tend to pay more attention to asphalt deposition, rather than the CNMCC variation at reservoir scale [12–15]. In fact, the latter is still not well understood during CO_2 flooding process in oil reservoirs. Generally, the differences in length and thickness between core and reservoir scales can result in different heterogeneity in horizontal and vertical directions. CO_2 channeling in flow

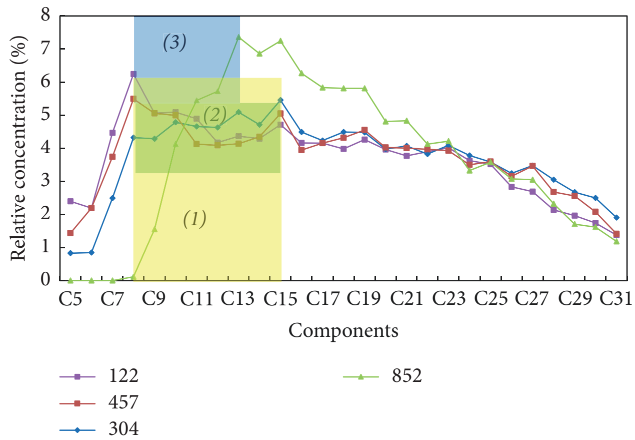


Figure 1: Relative concentration of produced oil compositions of production well W1 at different injection time.

direction at core scale is weaker than that at reservoir scale. Meanwhile, in vertical direction, CO_2 and oil at reservoir scale are mixed more thoroughly than at core scale. Based on these two main differences, it is reasonable to believe that the variation mechanism of CNMCC at reservoir scale would be quite different from that at core scale.

To investigate the CNMCC variation mechanism in CO_2 field flooding, this paper introduces a new concept "pulse characteristic" to characterize the CNMCC change law in produced oil, based on the field data. The physical process of displacement in heterogeneous formation is analyzed, and a scientific conjecture on the reason of the pulse characteristic of CNMCC at reservoir scale is proposed. Moreover, two numerical components models are established to validate the conjecture successfully. The pulse characteristic of CNMCC may provide a new way to identify and quantify the heterogeneity of CO_2 flooding reservoirs.

2. CNMCC Variation at Reservoir Scale

Based on the experimental results on CO_2 flooding [10, 11], it is believed that CNMCC should increase monotonically with CO_2 injection volume. However, CO_2 flooding pilot test at reservoir scale give us different results.

Composition analysis of produced oil from production well W1 in oil field H1 (China) has been performed. Figure 1 illustrates the relative component concentrations of produced oil at different time (from 122 to 852 days), in which x-axis shows components in oil phase and y-axis presents relative concentration. The relative component concentrations are calculated as normalized concentrations of components C5 to C31.

There is strong heterogeneity in the oil field H1, resulting from microcracks. The main parameters of the reservoir and fluid are listed in Table 1.

The commissioning date of production well W1 is one month before the commissioning date of corresponding injection well, which has a continuous CO_2 injection rate of 30 t/d. We set the commissioning date of corresponding injection well as the initial time; that is, injection time equals

Table 1: Main parameters of the reservoir and fluid.

Parameter	Values
Initial formation pressure	22.5 MPa
Formation temperature	88°C
Porosity	0.12
Permeability	5 mD
Initial oil saturation	0.56
Oil viscosity	0.44 mPa·s
Oil density	0.73
Flash gas oil ratio	$34\ m^3/m^3$
Bubble point	6.3 MPa
Minimum miscible pressure (MMP)	21.5 MPa

zero. The CNMCC variation of production well W1 can be divided into the following three stages (shown as three highlighted regions in Figure 1).

(1) From 122 to 304 days (pink and blue lines), the relative concentrations of compositions C5–C11 in produced oil decrease, while the relative concentrations of compositions C12–C16 increase. The corresponding CNMCC increases from C8 to C15. In this stage, the CNMCC has positive correlation with CO_2 injection volume, which coincides with the core experiments [10, 11].

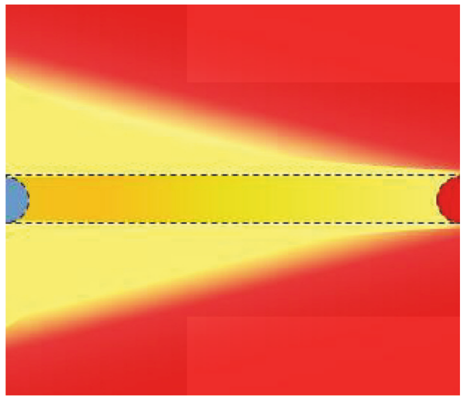
(2) From 304 to 457 days (blue and red lines), the relative concentrations of compositions C5–C10 in produced oil increase, while the relative concentrations of compositions C11–C16 decrease. In this stage, the CNMCC has negative correlation with CO_2 injection volume. It indicates the nonmonotonic variation of CNMCC in the reservoir scale.

(3) From 457 to 852 days (red and green lines), while the relative concentrations of compositions C5–C10 in produced oil decrease, the relative concentrations of compositions C11–C23 increase. The corresponding CNMCC of produced oil increases again from C8 to C13.

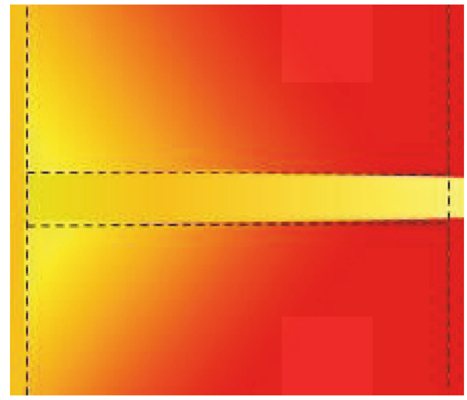
As shown in Figure 1, the CNMCC of production well W1 changes nonmonotonically with the CO_2 injection volume; that is, it increases at the beginning, then decreases later, and increases again. We propose the concept of "pulse characteristic" to describe the nonmonotonic variation of CNMCC at reservoir scale. To explain the mechanism of this phenomenon, we analyze the entire CO_2-oil interaction process in heterogeneous reservoir and provide our explanation in the next section.

3. Mechanism of Pulse Characteristic

According to the composition characteristics of produced oil, there are three main stages in the process of CO_2 flooding in homogeneous reservoirs [16–18]. The produced oil in the early stage is not in contact with CO_2, so its compositions are the same as the original oil compositions. In the middle stage, the produced oil is from the leading displacement edge, where mainly the light oil compositions occupy, because of the oil-CO_2 extraction and dissolution. The produced oil in the late stage mainly consists of the remaining oil and usually has heavy compositions. Since the characteristic of



(a) Plane map



(b) Vertical map

FIGURE 2: CO_2 (yellow) and oil (red) distribution and profile schematic diagram in the late stage.

the middle stage is not significant [11], the CNMCC increases monotonically with CO_2 injection volume at core scale.

However, the core scale usually exhibits lower heterogeneity than the reservoir scale. If there is plane heterogeneity, that is, CO_2 channeling-paths in the formation, the above three stages of CO_2 flooding would be different.

The main difference occurs in the late stage when CO_2 has occupied the whole CO_2 channeling-paths. The produced oil in this stage is mainly from outside of the channeling-paths, since CO_2 has displaced almost all the oil in the channeling-paths, as shown in Figure 2. This "fresh oil" has not been extracted thoroughly and still has quite a few light compositions. Therefore, the light compositions in produced oil will increase, which results in CNMCC decrease in the late stage. To sum up, the interaction degree between oil and injected CO_2 is not monotonic with time anymore under heterogeneous condition.

Based on the above analysis, we propose a conjecture to explain the CNMCC pulse characteristic at reservoir scale: the CNMCC will show back-and-forth pulse characteristic if there is plane heterogeneity in the reservoir, that is, channeling-paths. In the next section, this conjecture will be validated by two fully compositional models numerically.

4. Validation by Numerical Simulation

4.1. Fully Compositional Model Setting. To validate the conjecture in Section 3, we establish two fully compositional numerical models from Eclipse E300 module to simulate homogenous and heterogeneous scenarios, respectively. The heterogeneous model has an interwell channeling path which permeability is 100 mD. The corresponding formation and fluid parameters of the models are the same as those listed in Table 1. To investigate the components variation, we set 35 nonaqueous components in the models, including CO_2, N_2, C1–C32, and C32+. The oil compositions are shown in Table 2. The corresponding relative component concentrations are shown in Figure 3 (blue line), illustrating that initial CNMCC is C9.

According to the field flow regime, the development processes are depletion drive until formation pressure reaches 12 MPa, then water drive, and finally CO_2 drive development. In CO_2 flooding, the injection and production rates are constant (7500 sm^3/day and 2.5 rm^3/day, resp.). Based on the MMP in Table 1, it is miscible flooding near injection well and immiscible flooding away from injection well.

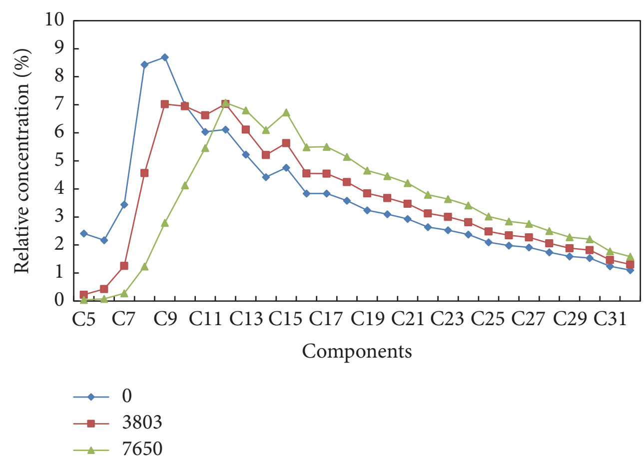


FIGURE 3: Relative concentration of produced oil at different time in the homogeneous model.

4.2. Simulation Results. Figure 3 shows the produced oil composition of the homogeneous model at different time. During CO_2 flooding process, the CNMCC increases monotonically from C9 to C12 with CO_2 injection volume. Although the CNMCC of produced oil are constant at C12 from injection time 3803 to 7650 days, we still observe the increasing relative concentration of heavy compositions and decreasing relative concentration of light compositions.

Figure 4 shows the produced oil composition of the heterogeneous model at different time. The CNMCC of produced oil increases from C9 to C30 during CO_2 injection time 0–210 days. After 210 days, the CNMCC of produced oil decreases from C30 to C12 until 788 days. Then the CNMCC of produced oil remains constant at C12. The nonmonotonic

TABLE 2: Oil component compositions in the models.

Component	Composition
CO_2	0.0035
N_2	0.0201
C1	0.1703
C2	0.06
C3	0.0392
C4	0.0173
C5	0.0241
C6	0.016
C7	0.0229
C8	0.0541
C9	0.0544
C10	0.0434
C11	0.0373
C12	0.0377
C13	0.0322
C14	0.0272
C15	0.0293
C16	0.0237
C17	0.0236
C18	0.0221
C19	0.02
C20	0.0191
C21	0.018
C22	0.0163
C23	0.0156
C24	0.0146
C25	0.0129
C26	0.0122
C27	0.0118
C28	0.0107
C29	0.0098
C30	0.0095
C31	0.0076
C32	0.0068
C32+	0.0567

variation of CNMCC only occurs in heterogeneous scenario, which is also observed in the field case shown in Figure 1.

5. Discussion

The CNMCC increases monotonically from C9 to C12 with CO_2 injection volume in the homogenous model, exhibiting the same change law with the experimental results [10, 11]. Based on the analysis in Section 3, it results from the monotonic variation of oil-CO_2 mixing degree in homogenous model.

The variation of CNMCC shows pulse characteristic in the heterogeneous model (Figure 4), which validates the conjecture in Section 3. Figure 5 presents the gas-oil ratio (GOR) and the oil saturation inside and out of the channel at the half of interwell distance.

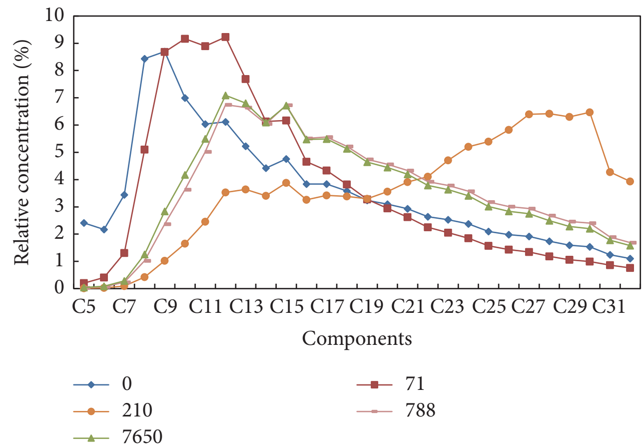


FIGURE 4: Relative concentration of produced oil at different time in the heterogeneous model.

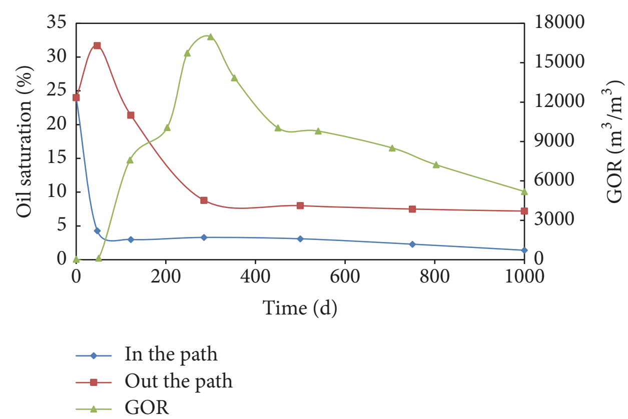


FIGURE 5: The oil saturation and GOR curves versus CO_2 injection time.

Before injection time 210 days, the produced oil is mainly from the channeling path, since the oil saturation in the path decreases rapidly (blue line). The mixing degree between oil and injected CO_2 is increased monotonically. Therefore, the CNMCC increases from C9 to C30 monotonically as well.

In the period of injection time 210–788 days, the produced oil is mainly from outside of the path, since the oil saturation out of the path decreases rapidly (red line). The interaction degree between the oil and injection CO_2 becomes nonmonotonic because the new oil enters and contributes to the produced oil. Therefore, the CNMCC decreases from C30 to C12 in this period.

The current work proposes a sufficient condition for pulse characteristic of CNMCC at reservoir scale. More intensive research needs to be conducted on the effects of other factors, including formation pressure, oil composition, and water saturation.

6. Conclusions

To investigate the CNMCC variation mechanism at reservoir scale, the present paper introduces the concept of pulse characteristic to describe the CNMCC change law in CO_2 flooding pilot test. Two fully compositional numerical models are established to validate the conjecture on the pulse characteristic. The main conclusions are drawn as follows.

(1) The CO_2 flooding field data exhibits pulse characteristic; that is, the CNMCC of produced oil increases in the early stage, then decreases, and increases again in the late stage. It is different from the monotonic increasing characteristic at core scale.

(2) The pulse characteristic of CNMCC only occurs in heterogeneous formation, resulting from the nonmonotonic change of interaction degree between oil and injected CO_2. It is validated by simulation results of the two fully compositional models.

(3) A new method may be developed to identify and quantify the reservoir heterogeneity, using the idea of pulse characteristic of CNMCC, since it contains the information of CO_2 channeling path.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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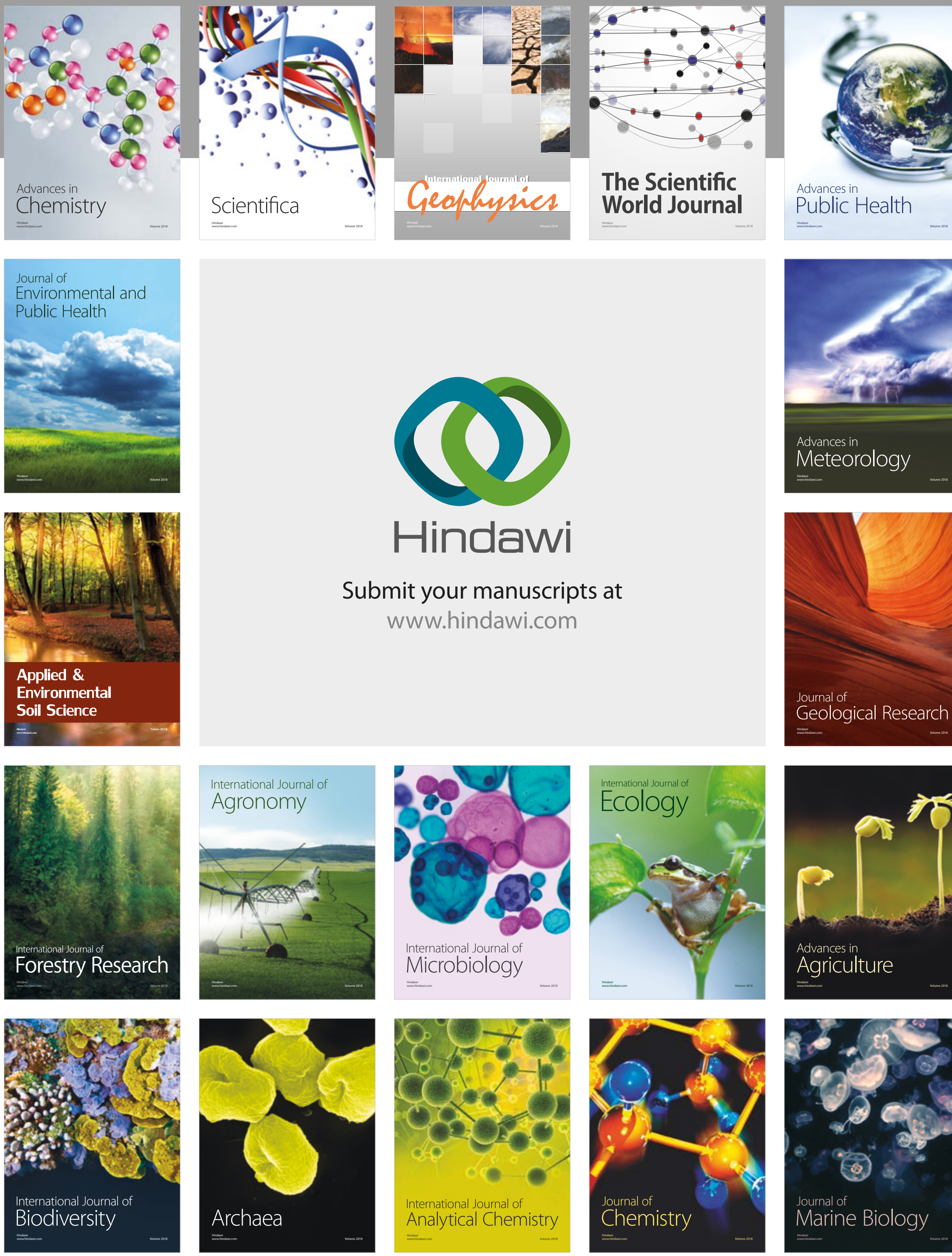
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