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ORIGINAL ARTICLE

Diagenetic evolution of clastic reservoirs and its records in fine subsection: significance and application

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Abstract It was showed that understanding of the diagenetic modifications and its associated products in the deeply to ultra-deeply buried tight sandstone reservoirs (DUDTSR) is great important for reservoir characterization and hydrocarbon prediction. However, the fine characterization of diagenetic evolution via geologic modelling in tight sandstones remains a great challenge as for complexity of lithology, temperature, pressure and formation fluid throughout the entire life cycle of tight sandstone reservoirs. To help get a comprehensive idea of the distribution of diagenetic processes on the formation of DUDTSR in the long geological period, type-I and type-II fine sections of diagenetic stage for clastic reservoirs were creatively proposed and its essence was illustrated using the Paleogene Huagang (E_3H) Formation in the southern Xihu Sag. Through combination of both quantitative and qualitative methods which began with current formation temperature, vitrinite analysis, illite and I/S mixed layers based on analytical testing of the E_3H Formation, (1) Paleotemperature (T), vitrinite reflectivity and smectite in mixed layer during burial processes were restored based on numerical analysis, (2) The accurate division of diagenetic evolution was identified from coarse to fine process using new model, (3) And finally the geological significance of fine division of the conventional diagenetic stage was illustrated for low-porosity and tight sandstone reservoirs.

Keywords Tight sandstone reservoirs · Diagenetic evolution · Fine subsection · Significance

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1 Introduction

At present, the petroleum resources of deeply to ultra-deeply buried tight sandstone reservoirs (DUDTSR) with porosity of less than 10% and intrinsic permeability less than 0.1 mD (SY/T6832-2011) have become an important source of global energy development (Ajdukiewicz et al. 2010; Zou et al. 2018; Qian et al. 2022). Substantial efforts have been made to help get a better know of diagenetic processes and associated products in DUDTSR because of the belief that these physical and chemical alterations are great important for reservoirs quality and overall heterogeneity (Morad et al. 2000; Mahmic et al. 2018; Meng et al. 2020). It has been evidenced that grains contacting relationship, pore structure, diagenetic minerals, diagenesis, diagenetic strength, fluid properties and organic compound generating capability in burial processes are closely connected with diagenetic stages (Wilson and Stanton, 1994; Meng et al. 2008; Ajdukiewicz et al. 2010; Mahmic et al. 2018), and thus the detailed description of these processes is critical to successful exploration in oilfield. It was confirmed for the first time in the late 1970s that diagenetic evolution had stage characteristics (Schmidt and McDonald 1979). In the early 1990s, Ying (1992) came up with the classification basis and nomenclature method of diagenetic stages through combination of quantitative and qualitative methods which comprehensively use paleotemperature, grains contacting relationship, pore texture, vitrinite analysis, clay minerals and quartz secondary enlargement index (Ying et al. 2003; Ajdukiewicz et al. 2010; Mahmic et al. 2018; Xu et al. 2020; Qian et al. 2020a) (Table 1). More recently, Meng et al. (2020) have further subdivided diagenetic stage IIA of clastic reservoirs into four diagenetic sub-stages using vitrinite reflectance as the characteristic parameter. Diagenetic processes and associated products can extensively affect the reservoir quality of sandstones (Ajdukiewicz et al. 2010; Mahmic et al. 2018), notably the DUDTSR with high degree of diagenetic stage (Qian et al. 2020a). To better understand the distribution of diagenetic modifications on the formation of DUDTSR in the burial processes, fine section of diagenetic stage for clastic reservoirs were proposed, hoping to provide an efficient approach for evaluation and prediction of the DUDTSR in Xihu sag.

2 Geological setting

Xihu Sag with an area of 5.9×10^4 km^2 is the largest offshore sag in the East China Sea Shelf Basin (ECSSB), which is divided into five tectonic units from west to east (Zhou et al. 2001; Jiang 2003; Zhu et al. 2019; Xu et al. 2020; Qian et al. 2020c). During the past 50 years, the Eocene Pinghu (E_2P) Formation and Oligocene Huagang (E_3H) Formation as the main target layers have been discovered with large oil and gas resources in the exploration of this sag. The target layer E_3H Formation with a depth 2000–6000 m (av. 3600 m) was discovered tight oil and gas resources with porosity $< 10\%$ and permeability < 1mD, accounting for nearly 80% of the whole resources (Jiang 2003; Zhu et al. 2019), which is a vital gas producing formation in this sag (Qian et al. 2020a; Xu et al. 2020; Wang et al. 2020). It was petrographically showed that the lithology in the Xihu Sag consists of gravelly sandstone to oil shale, most of which are coarse-grained sandstone, medium-grained sandstone, fine-grained sandstone, and mudstone. This article, equipped with diagenetic dynamics, intends to develop a new method with further subdivide the diagenetic stage on the basis of current diagenetic stage division criterion of oil and gas industry, and provide scientific basis for the exploration and development of conventional oil and gas and tight oil and gas in different basins in China.

3 Methods and samples

In this study, geological parameters of paleotemperature, vitrinite analysis (*Ro%*) and illite and I/S mixed layers were synthetically used to recognize the diagenetic processes of the E_3H Formation and 14 wells were selected for this research. The burial history and thermal history of E_3H Formation were executed by petrelmod 2013 software, and then *Ro%* at various historical times was calculated by using a chemical kinetic principle, which was proposed by Sweeney and Burnha (1990), while the conversion process from smectite to illite (I/S–S%) was calculated by Elliot's model equation (Elliott and Edenfield 1999).

The study of diagenetic system for hydrocarbon exploration in oil and gas bearing basins usually pays more attention to the geological process and its intensity on pore evolution on time scale. The inhomogeneity of DUDTSR and the complexity in oil–gas concentration offer a challenge to reservoirs prediction, and the linear relationship between buried depth and geological parameters is usually not strong. Therefore, a subdivision scheme for diagenetic stages of clastic reservoirs is innovatively proposed, which can be used to fine geologic processes and precisely reveal the key geological factors leading to the differential evolution of reservoirs. Based on the scheme proposed by Ying et al. (2003), smaller paleotemperature scale is selected to explain the border conditions of other parameters. At the same time, in order to reflect the accuracy of subdivision scheme, two paleotemperature scales were selected and two fine subdivision schemes were established (DFI and DFII). In type-I fine subsection scheme (Qian et al. 2020c), the diagenetic stages (eodiagenesis, mesodiagenesis, and teleodiagenesis) in burial processes are subdivided into 19

Table 1 Correspondence between the indexes of clastic different diagenetic stages (2003 by Ying et al.)

Diagenetic stages		Paleo temperature (°C)	Organic matter *Ro%*	Mudstone I/S–S%
Eodiagenesis	IA	≤ 65	< 0.35	> 70
	IB	$> 65 \sim 85$	$0.35 \sim 0.5$	$70 \sim 50$
Mesodiagenesis	IIA	$> 85 \sim 140$	$0.5 \sim 1.3$	$50 \sim 15$
	IIB	$> 140 \sim 175$	$1.3 \sim 2.0$	< 15
Teleodiagenesis	III	> 175	$2.0 \sim 4.0$	Disappear

stages (DFI1- DFI19) at interval of 10 °C, and the border conditions of *Ro%* and I/S–S% are explained. Among them, DFI1- DFI5 is approximate equal of the early eodiagenesis (IA), while DFI6-DFI8, DFI9-DFI10, DFI11-DFI13, DFI14-DFI17 and DFI18-DFI19 are roughly equal to the stages of the late eodiagenesis (IB), mesodiagenesis (including IIA1, A2, IIB) and teleodiagenesis (III) individually. In type-II fine subsection scheme, the diagenetic stage is subdivided into 36 stages (DFII1-DFII36) at interval of 5 °C (Qian et al, 2020a, c), and the border conditions of *Ro%* and I/S–S% are also explained. Among them, DFII1-DFII9 is equal of the early eodiagenesis (IA), while DFII10-DFII13, DFII14-DFII19, DFII20-DFII24, DFII25-DFII31 and DFII32-DFII36 are equivalent to the stages of the late eodiagenesis (IB), mesodiagenesis (including IIA1, IIA2, IIB) and teleodiagenesis (III) separately.

In the research process, with the help of deepening from macro to micro, and considering the regional burial history, thermal history, pressure history and fluid history of sedimentary basin, the reservoir diagenesis type, diagenetic stage evolution process and diagenetic evolution sequence under different order sequences are reproduced. From DFI to DFII, it is a process of continuous refinement of diagenetic evolution simulation.

4 Results and discussion

4.1 Sensitivity of different parameter

The DS-*Ro%* value indicates the following features (Fig. 1): (1) The value increases with depth; (2) Its change is very slow in shallow buried stage ($H < 1000$ m, $T < 60$ °C) and deep buried stage ($H > 2000$ m, $T > 100$ °C), but is relatively equable in middle buried stage ($H < 2000$ m, $T < 100$ °C); (3) The thermal evolution of vitrinite formation in geological history is irreversible, and there is no backtracking (Ying et al.2003). The DS-I/S–S% values demonstrate following characteristics (Fig. 1): (1) It changes relatively slow in shallow buried stage and deep buried stage, but evolves rapidly in middle buried stage; (2) Its value increases with depth; (3) The development of I/S–S% is irreversible. DS-T value points out the subsequent characteristics: (1) It is easy to be affected by tectonic uplift; (2) It changes relatively equable in the shallow and middle buried stage, but very slow in the deep buried stage (Fig. 1). The simulation results show that I/S–S% is relatively accurate in describing diagenetic evolution stage in shallow burial stage, while DS-I/S–S% is smaller in deep burial stage. It is more conservative that the simulation result of T index compared to measurements under some conditions, while the simulation result of *Ro%* is relatively less. The simulation results of I/S–S% have the above two exists which is influenced by changes in burial depth, paleotemperature, time of duration, pressure and some chemical variables of synchronization or asynchronization (Qian et al. 2020b). Therefore, it is difficult to characterize the diagenetic evolution stage with a single parameter like paleotemperature or vitrinite reflectance.

Diagenesis is both the physical and chemical changes of sediments under lower temperature (less 200 °C), which is affected by a variety of factors such as basin type, provenance, tectonic background, temperature, time, pressure and fluid (Xu et al. 2020; Qian et al. 2020c). There are several parameters that can affect the diagenetic stage division of reservoir: clastic particles, pore texture, authigenic mineral assemblage (quartz, carbonate minerals), vitrinite reflectance (*Ro%*) (Meng et al. 2020; Qian et al. 2020b), organic matter decomposition peak temperature (Tmax) (Tong et al. 2009), proportion of I/S–S% (Bühmann 1992; Qian et al. 2020b), and quartz index (Ying et al. 2003; Meng et al. 2020; Qian et al. 2020b). In order to quantitatively study diagenesis evolution, it is necessary to select indicators with higher accuracy and stronger applicability. Among the qualitative and quantitative indicators, *Ro%* can accurately reflect the effect of the combined effect of time and temperature (Xiao et al. 1995), and clay minerals are widespread minerals in clastic rocks. When a single parameter is used, the simulation results are not accurate, so it is necessary to use multiple parameters comprehensively.

4.2 Diagenetic evolution

Through the vertical distribution of palaeotemperature (T), *Ro%*, I/S–S%, it was evidently identified that the Oligocene Huagang (E_3H) Formation has experienced four burial characteristic: slow subsidence period, rapid subsidence period, structural uplift period, stable subsidence period. It can be observed that the plastic components (feldspar, mica and clays) have been severely deformed and oriented by strong mechanical compaction through the microscope observation (Fig. 2A–B). Additionally, the contacts between the particles in the rock indicate that the rock experienced stronger compaction in the Huagang formation (Fig. 2C–E). The data have confirmed that the reservoir of the E_3H Formation is mainly in the early- and late- stage of mesodiagenesis (IIA-IIB) and that depth ranging from 2500 to 3500 m is in the stage IIA1, while depth ranging from 3500 to 4500 m is in the stage IIA2 and 4500–5000 m is in the late stage of mesodiagenesis (IIB). A complete series of diagenetic evolution of the E_3H Formation tight sandstone is: (1) Early mechanical compaction and significant cementation of calcite and gypsum in alkaline diagenetic environment; (2) Medium-term acidic formation fluids

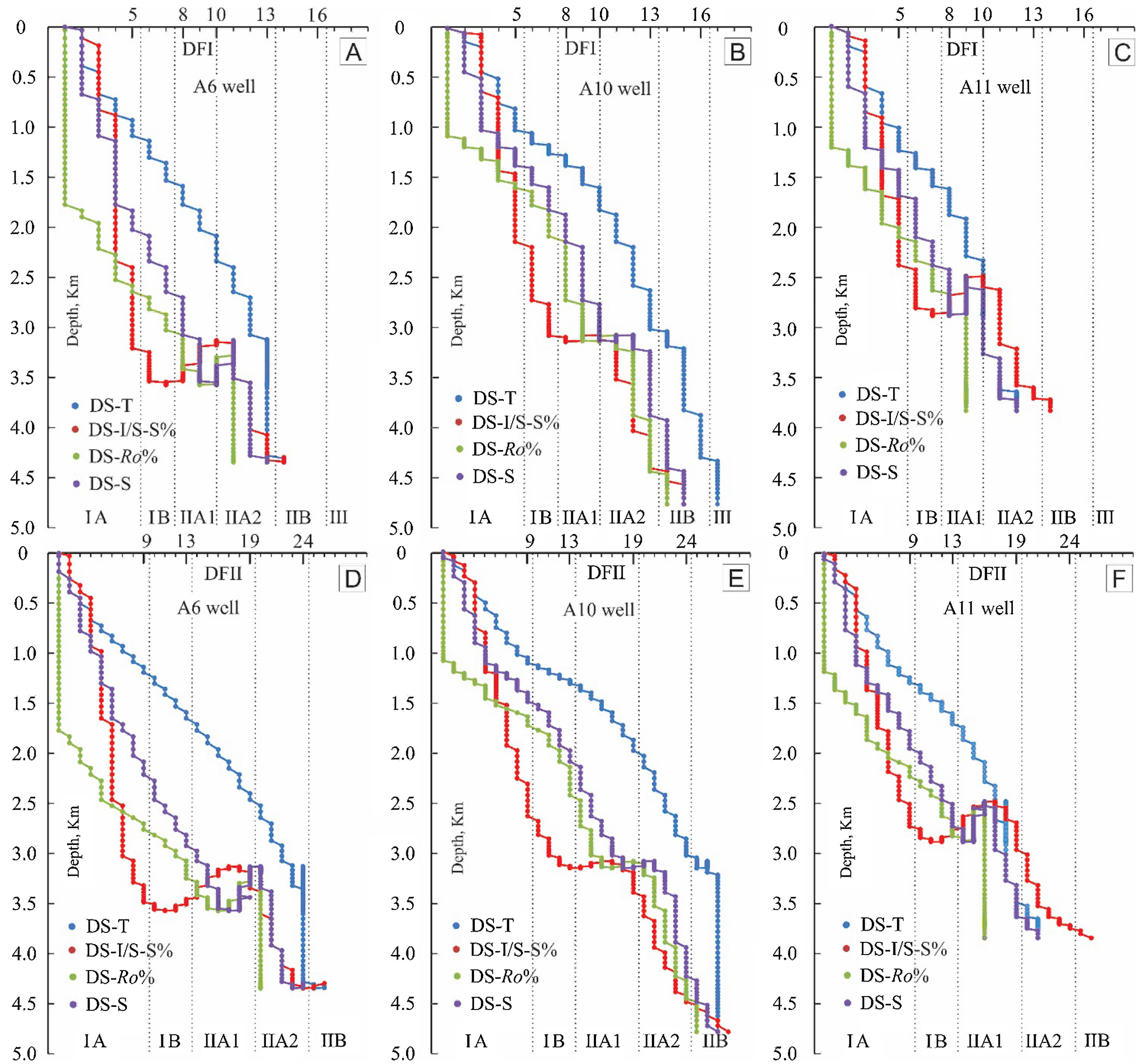

Fig. 1 Comparative analysis of diagenetic stages using different geological parameters for type-I and type-II fine subsection scheme

leading to widespread dissolution of feldspar and carbonate cements; (3) Late cementation of clay minerals and ankerite. The combined effects of compaction, cementation and dissolution in burial history determined the commercial viability of the Huagang Formation tight sandstone reservoir (Xu et al. 2020).

4.3 Geologic significance of DFI and DFII

The geological process and its intensity on pore evolution usually take place in a very short time and a very small volume, such as several 10 ka in time and a few meters to several hundreds of meters in scale. By understanding the meaning of various parameters in temporal and spatial domain, including paleotemperature (T), vitrinite reflectance (*Ro*%), the highest pyrolysis peak temperature (Tmax), thermal alteration index of the proportion of smectite in illite/smectite interstratified minerals (I/S–S%) and authigenic minerals assemblage, the diagenetic stage can be accurately divide (Ying 1992; Meng et al. 2008; Qian et al.2020b). The Oligocene sandstone reservoirs in the Xihu Sag experienced the late Oligocene Huagang movement and the late Miocene Longjing movement (Hao et al. 2018), leading to great difference of the Huagang Formation depth ranging from 2200 to 5500 m at present day and strong heterogeneity as for complex diagenesis

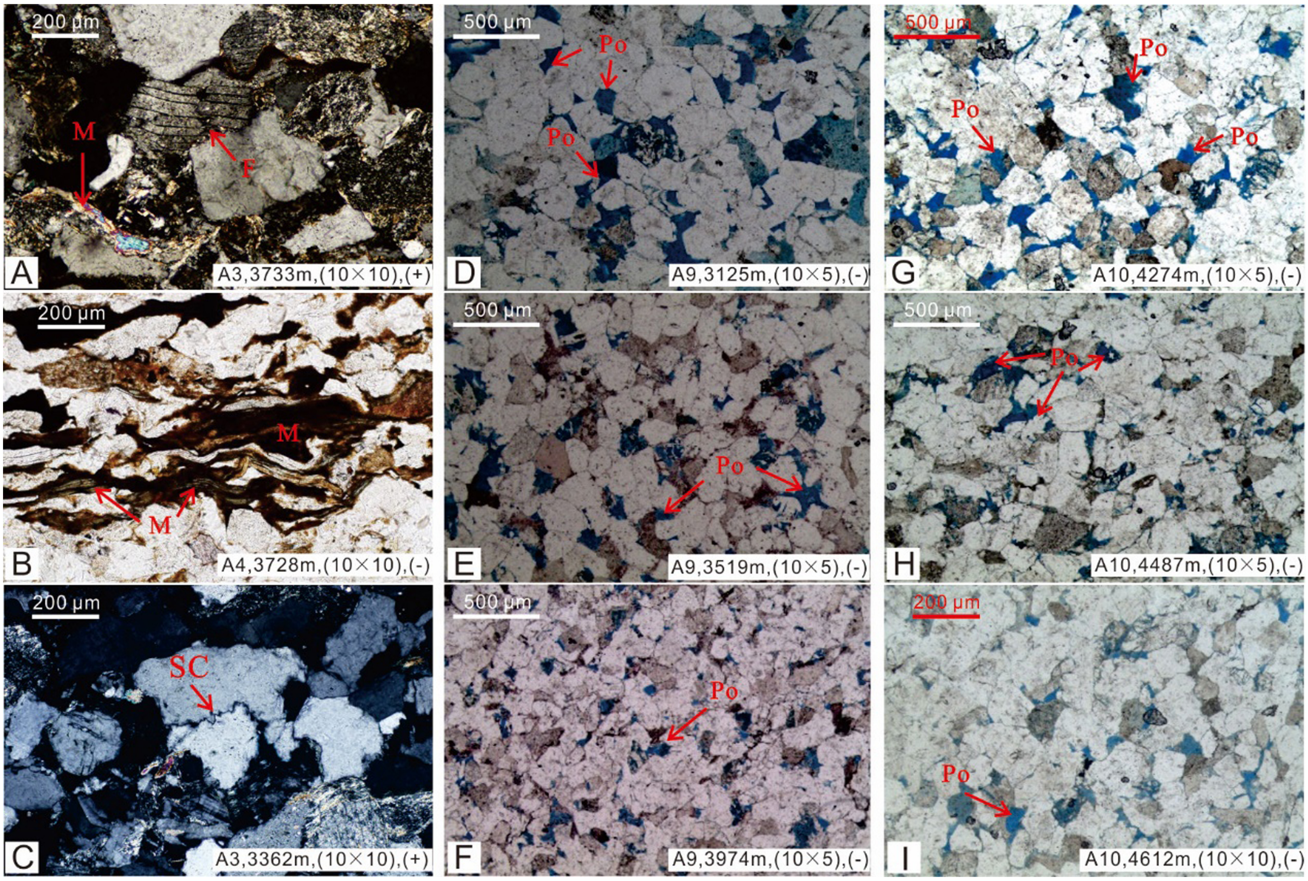

Fig. 2 Characteristics of reservoir compaction of Huagang Formation in Xihu sag. F-Feldspar; M-Mica; LC-Line contact; CC-Concavo-convex contact; SC-Suture contact. Po- Pores

transformation in the process of burial (Wang et al. 2020). This fine division schemes used to identify the diagenetic evolution stages of the Huagang Formation can highlight the diversity of reservoir evolution processes (diagenetic environment, diagenetic event, diagenesis, diagenetic minerals, diagenetic strength, diagenetic fluid, expulsion time and intensity from source rock, diagenetic reservoir-forming process and their relationship) and help to reveal the crucial geological factors linked to the differential evolution of clastic reservoirs in deep burial and high diagenetic stages. Future refinement study of DF and its geological significance in this study will require other pollen-color alteration data and mudstone experiment based on thermal simulation to evaluate accurate diagenetic evolution simulation.

5 Conclusions

(1) Type-I and type-II fine subsection of diagenetic stage (DFI and DFII) were put forward based on paleotemperature, vitrinite analysis and proportion of illite in I/S mixed layers. In type-I fine subsection scheme, the diagenetic stage was subdivided into 19 stages at interval of 10 °C, while 36 stages at interval of 5 °C was identified in type-II fine subsection scheme.

(2) DS-*Ro*%, DS-I/S–S% and DS-T show different sensitivity in diagenetic stage division of Huagang Formation. To precisely explain the diagenetic stages, it is better to combine T, *Ro*% and I/S–S% together.

(3) A fine subsection of diagenetic stages can emphasize the variations of reservoir evolution processes and help to recognize the critical geological components associated with the various evolution of clastic reservoirs in deep burial and high diagenetic stages.

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Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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