ARTICLE IN PRESS

Marine and Petroleum Geology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Diagenetic constraints on the heterogeneity of tight sandstone reservoirs: A case study on the Upper Triassic Xujiahe Formation in the Sichuan Basin, southwest China

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A R T I C L E I N F O

Keywords:
Diagenesis
Reservoir heterogeneity
Tight sandstone
Xujiahe Formation
Sichuan Basin

A B S T R A C T

Heterogeneity is an essential feature of tight sandstones because it is directly related to reservoir quality. The Upper Triassic Xujiahe Formation in the Sichuan Basin was used as a case study to analyse the diagenetic constraints on the heterogeneity of tight sandstone reservoirs. The three main diagenetic processes of interest are mechanical compaction, cementation, and dissolution. A dissolution facies, quartz cement facies, and carbonate cement facies present sequentially from the centre to the margin of sand bodies. Abundant feldspars and rock fragments were dissolved to form secondary porosity or filled by carbonate cement. Authigenic chlorite coatings, generated from eogenesis to the deep burial stage, are thickest in high-porosity-samples. The $\delta^{13}C$ of carbonate cement ranges from −10.56‰ to 1.15‰ (PDB), suggesting multiple sources of carbon, including carbonate fragments, early inorganic carbonate cement, and organically derived CO_2. Based on $\delta^{18}O$, carbonate cementation occurred from 33 °C to 110 °C. Microthermometric data of aqueous inclusions indicate that quartz cement precipitated at a temperature range of 120 °C–140 °C.

A summary model of the diagenetic constraints on the heterogeneity of sandstones was constructed. The spatial distribution of digenetic facies is controlled by differences in fluid flow velocity and pH. Fluids, especially hydrocarbons, migrated preferentially within the centre of sand bodies, and caused dissolution. Dissolution generated secondary porosity and provided materials for authigenic mineral precipitation. Carbonate fragments were better preserved and superimposed with later carbonate cement along the sandstone-mudstone boundary. Quartz overgrowths formed after carbonate cementation, and developed in the transition zone between the intervals of carbonate cementation and dissolution. Consequently, the reservoir quality of the Xujiahe sandstones decreases gradually moving from the centre to the margin of the sand bodies.

1. Introduction

As conventional hydrocarbon resources dwindle and global energy requirements rise, unconventional resources, including tight oil, tight gas, shale gas, heavy oil, and gas hydrates, are becoming increasingly important (Arthur and Cole, 2014). Tight gas sandstone, generally defined as having porosity less than 10% and permeability less than 0.1 mD (Law and Curtis, 2002; Holditch, 2006; Zou et al., 2012), is one of the most abundant and prospective unconventional resources (Zou et al., 2012, 2013). Reservoir quality and fluid migration are controlled by reservoir heterogeneity (Weber, 1982; Morad et al., 2010). Characterizing reservoir heterogeneity is of prime importance for resource evaluation and planning efficient hydrocarbon production strategies (Hamilton et al., 1998; Dutton et al., 2002; Henares et al., 2016). Hence, understanding the mechanisms of reservoir heterogeneity and modelling them have become a common focus of tight sandstone reservoir studies.

Sandstone reservoir heterogeneity is commonly attributed to variations in depositional facies (Higgs et al., 2010; Morad et al., 2010; Khalifa and Morad, 2015). Depositional facies control: 1) sand-body geometry, mud-sand ratio, reservoir architecture, mineral composition, grain size, and sorting; 2) the primary porosity, permeability, and pore

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https://doi.org/10.1016/j.marpetgeo.2017.11.027
Received 1 August 2017; Received in revised form 13 October 2017; Accepted 27 November 2017
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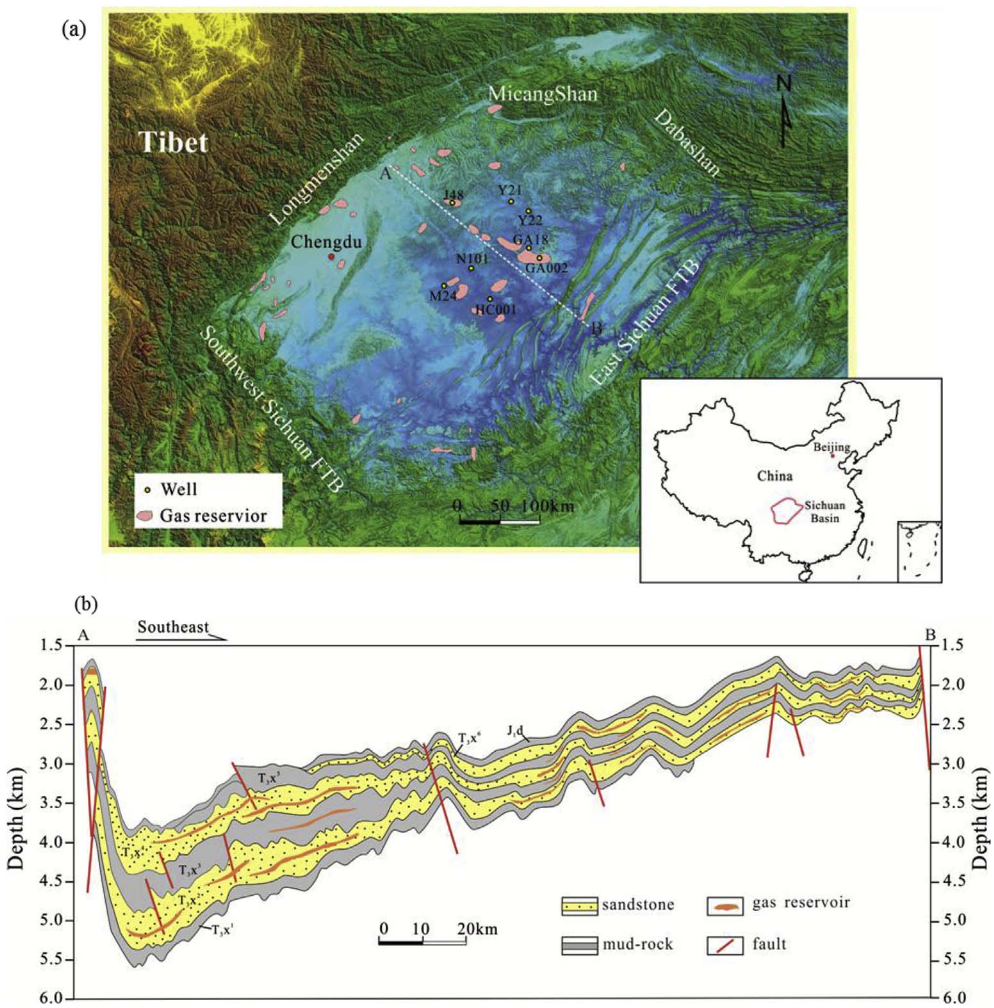

Fig. 1. (a) Map of the Sichuan Basin and the surrounding mountains and fold thrust belts (FTB). Background elevation image was produced from SRTM data V4 (available from http://srtm.sci.cgiar.org). Locations of the main Upper Triassic gas reservoirs are from Dai et al. (2009). Locations of wells that were selected for observation of the whole core and selection of samples are shown on the map. (b) Cross-section of the Upper Triassic Xujiahe Formation in the Sichuan Basin (after Dai et al., 2009). The location of the profile is shown in (a).

water chemistry; 3) the distribution of eogenetic and mesogenetic alterations (Morad et al., 2000, 2010; Bjørlykke, 2014; Khalifa and Morad, 2015; Saïag et al., 2016). High-quality reservoirs typically develop in sandstones deposited in high-energy environments, such as distributary channels. These sandstones are characterized by coarse grain size, high degree of sorting, and little to no matrix. In contrast, sandstones deposited in low-energy environments, such as distributary mouth bars and sheet sand facies, are characterized by fine grained size, high matrix content, and low primary porosity (Zhou et al., 2016). Morad et al. (2010) linked the types and distribution of diagenetic processes to depositional facies and sequence-stratigraphic framework of clastic successions. The mechanical and chemical stability of sandstones strongly depends on grain composition (De Ros et al., 1994; Morad et al., 2010). Porosity in sandstones containing large amounts of ductile fragments (e.g. volcanic or mudstone fragments, biotite) reduces rapidly with increasing depth (Morad et al., 2010; Zhou et al., 2016). Feldspar and carbonate fragments are chemically unstable. Dissolution and secondary porosities tends to develop in sandstones with high feldspar and carbonate fragments content (Morad et al., 2000, 2010).

Diagenesis has significant impact on reservoir quality, but diagenetically induced heterogeneity is rarely assessed (Taylor et al., 2010; Henares et al., 2016; Ma et al., 2016; Rahman and Worden, 2016). Diagenetic processes, such as mechanical compaction and chemical alterations, affect the preservation of primary porosity and the development of secondary porosity. Mechanical compaction is the main factor that controls sandstone properties from the surface to the subsurface at a temperature lower than 70°C–80 °C (Bjørlykke, 1999; Bjørlykke and Jahren, 2012). Chemical diagenesis or fluid-rock interactions affect sandstone porosity and permeability during deep burial (high temperature, generally greater than 80 °C). Chemical diagenesis in clastics rocks mainly involves feldspar and fragment dissolution, carbonate cementation, quartz cementation, and authigenic clay mineral precipitation (Morad et al., 2010; Yuan et al., 2015; Rahman and Worden, 2016). The nature of the fluid source and fluid flow patterns affect the intensity of dissolution, distance of mass transfer, and precipitation sites, all of which can significantly intensify the reservoir heterogeneity (Lynch, 1996; Morad et al., 2000; Day-Stirrat et al., 2010; Higgs et al., 2013; Ma et al., 2016; Saïag et al., 2016).

As several gas fields have been discovered in recent years in the Upper Triassic Xujiahe Formation in the Sichuan Basin of southwest China, which is becoming one of the country's major areas of interest for gas exploration and research (Du, 2011). The Xujiahe Formation occurs at a depth of 2000–3000 m in the Sichuan Basin, but reached a maximum burial depth of ~5000 m before the Late Cretaceous tectonic uplift (Liu et al., 2012). Accordingly, the Xujiahe sandstones have a complex diagenetic history, as reflected by their high degree of heterogeneity. Previous petrographic studies have found that mechanical compaction, quartz cementation, carbonate cementation, authigenic clay mineralization, and dissolution are the main diagenetic processes that have affected the quality of the Xujiahe reservoirs (Lü and Liu, 2009; Zhu et al., 2009a; Zhang et al., 2011). However, little work has been done on the spatial distribution of diagenetic facies and the mechanisms of fluid–rock interactions in the Xujiahe Formation.

The main purpose of this paper is to characterize the diagenetic facies of the Xujiahe sandstones, determine their spatial distribution,

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