Geoscience Frontiers xxx (2016) 1–15

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

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

Research paper

Lithofacies paleogeography mapping and reservoir prediction in tight sandstone strata: A case study from central Sichuan Basin, China

Yuan Zhong [a,b], Lu Zhou [a,b], Xiucheng Tan [a,b,*], Chengbo Lian [b], Hong Liu [b], Jijia Liao [b], Guang Hu [b], Mingjie Liu [b], Jian Cao [c]

[a] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China
[b] Department of Earth Science and Technology, Southwest Petroleum University, Chengdu 610500, China
[c] School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China

ARTICLE INFO

Article history:
Received 3 May 2016
Received in revised form
23 August 2016
Accepted 7 September 2016
Available online xxx

Keywords:
Sand-rich strata
Reservoir "sweet spot"
Paleogeomorphology
Primary distributary channel
Lithofacies paleogeography

ABSTRACT

Sand-rich tight sandstone reservoirs are potential areas for oil and gas exploration. However, the high ratio of sandstone thickness to that of the strata in the formation poses many challenges and uncertainties to traditional lithofacies paleogeography mapping. Therefore, the prediction of reservoir sweet spots has remained problematic in the field of petroleum exploration. This study provides new insight into resolving this problem, based on the analyses of depositional characteristics of a typical modern sand-rich formation in a shallow braided river delta of the central Sichuan Basin, China. The varieties of sand-rich strata in the braided river delta environment include primary braided channels, secondary distributary channels and the distribution of sediments is controlled by the successive superposed strata deposited in paleogeomorphic valleys. The primary distributary channels have stronger hydrodynamic forces with higher proportions of coarse sand deposits than the secondary distributary channels. Therefore, lithofacies paleogeography mapping is controlled by the geomorphology, valley locations, and the migration of channels. We reconstructed the paleogeomorphology and valley systems that existed prior to the deposition of the Xujiahe Formation. Following this, rock-electro identification model for coarse skeletal sand bodies was constructed based on coring data. The results suggest that skeletal sand bodies in primary distributary channels occur mainly in the valleys and low-lying areas, whereas secondary distributary channels and fine deposits generally occur in the highland areas. The thickness distribution of skeletal sand bodies and lithofacies paleogeography map indicate a positive correlation in primary distributary channels and reservoir thickness. A significant correlation exists between different sedimentary facies and petrophysical properties. In addition, the degree of reservoir development in different sedimentary facies indicates that the mapping method reliably predicts the distribution of sweet spots. The application and understanding of the mapping method provide a reference for exploring tight sandstone reservoirs on a regional basis.

1. Introduction

Tight sandstone gas is an important unconventional hydrocarbon resource and many studies have been carried out on the tight sandstone gas reservoirs (Masters, 1984; Zhu et al., 2008; Zou et al., 2009; Ye et al., 2011; Mousavi and Bryant, 2012; Prodanović et al., 2013; Guo et al., 2013a; Gong et al., 2015; Lü et al., 2015; Xiao et al., 2015; Poszytek and Suchan, 2016; Wang et al., 2016). Large-area sand-rich strata are common and important features of tight sandstone reservoirs, such as in the Cretaceous Frontier Formation and the Mesaverde Formation in the Green River Basin in the USA, where the sandstones form as a result of deposition in vertically superimposed and horizontally contiguous deposits of large rivers and deltas. In China, tight sandstone reservoirs are horizontally contiguous and widely distributed in the lower Permian Shanxi Formation and the lower Shihezi Formation, as well as being

* Corresponding author. State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China.
E-mail address: tanxiucheng70@163.com (X. Tan).
Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2016.09.002

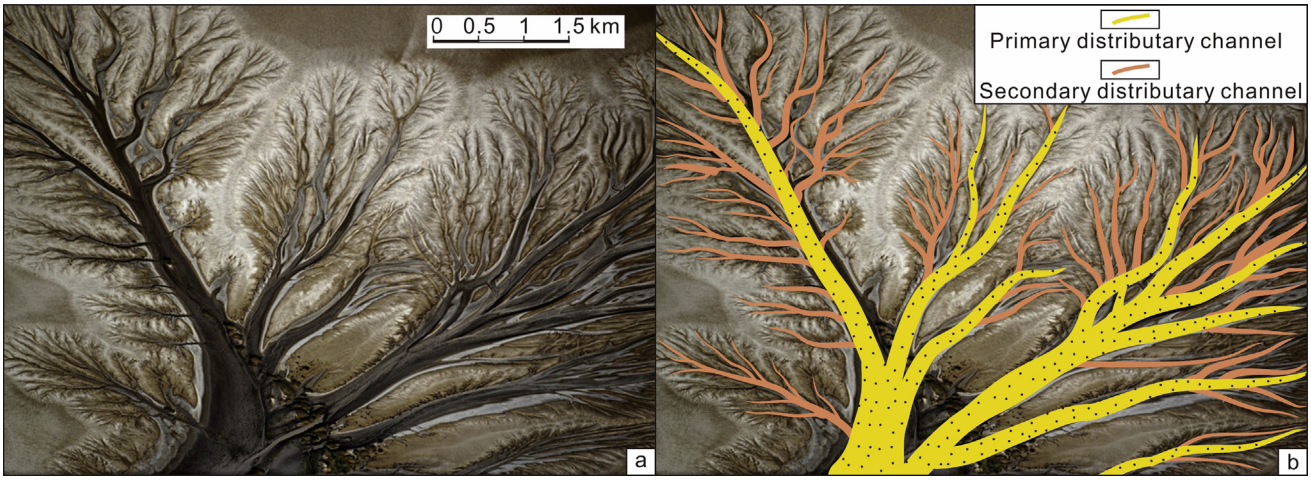

Figure 1. Example and interpretations of modern braided river delta deposits. (a) Dry braided river delta in the Kimberley region in northwest Australia; (b) interpretations of primary and secondary distributary channels in the delta (after: http://i1342.photobucket.com/albums/o771/zhangtuchuang/dilizhazhi/20121025011702921_zps4d9f9923.jpg).

extensively distributed in the Xu-2, Xu-4, and Xu-6 of the Xujiahe Formation (Tong et al., 2012). Currently, sweet spots in reservoirs in tight sandstone strata are predicted on the basis of high-precision geophysical methods and practices (Yang et al., 2004; Chen et al., 2009; Yu et al., 2010; He et al., 2011; Khair et al., 2013; Yang et al., 2013; Liu, 2014; Si et al., 2015; Zhou et al., 2015; Zhu et al., 2015). However, reservoir prediction cannot fully depend on this methodology, given the limits of the precision of seismic data and the technology available in most reservoir areas. Therefore, from a sedimentological perspective, lithofacies paleogeographic maps that reflect depositional environments are necessary for the exploration of favorable reservoir zones (Shinn et al., 2014; Ding et al., 2015). However, the high sand/formation ratios of sand-rich strata make traditional lithofacies paleogeographic maps inadequate for subtle microfacies classification and for effectively guiding predictions of the location of reservoir sweet spots, and hence sweet spot prediction has remained problematic in the field of petroleum exploration.

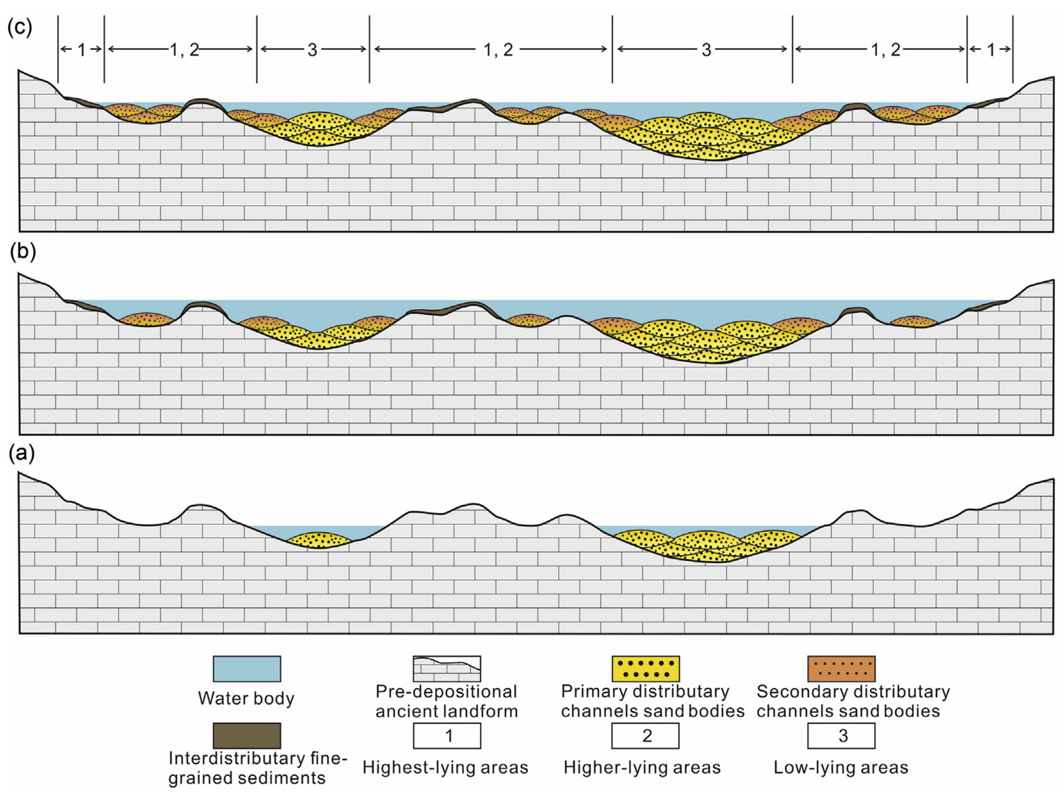

Figure 2. Depositional patterns of primary and secondary distributary channels. (a) During the initial stage of deposition, coarse-grained sand bodies are deposited in primary distributary channels in low-lying areas; (b) as the base level rises, fine-grained sand bodies are deposited in secondary distributary channels in higher areas, whereas muddy sediments are deposited in high interdistributary areas; (c) as the base level descends, the paleogeomorphology gradually levels up as low-lying areas are the sites of deposition of primary distributary channel sand bodies whereas high-lying areas are the sites of deposition of secondary distributary channel sand bodies.

Please cite this article in press as: Zhong, Y., et al., Lithofacies paleogeography mapping and reservoir prediction in tight sandstone strata: A case study from central Sichuan Basin, China, Geoscience Frontiers (2016), http://dx.doi.org/10.1016/j.gsf.2016.09.002

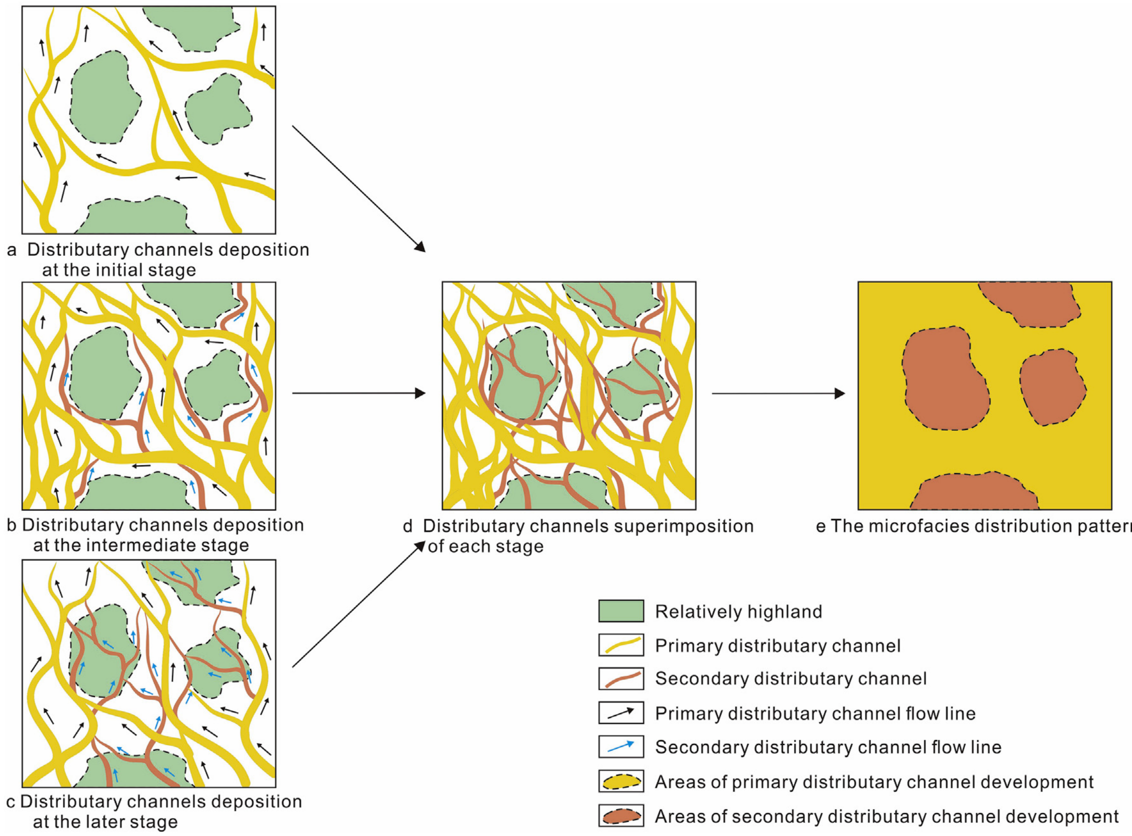

Figure 3. Superimposition on a plane of distributary channels, and distribution model of sedimentary microfacies.

Based on analyses of the depositional characteristics of modern sand-rich strata, the current study provides a new method of lithofacies paleogeography mapping of tight sand-rich sandstone reservoirs and the prediction of sweet spots. The new method is applied to an analysis of the Xu-2 in the Hechuan area, Sichuan Basin. The Xujiahe Formation in the Sichuan Basin is an important exploration area for tight sandstone gas and oil (Xie et al., 2008; Zeng et al., 2009; Wei et al., 2010; Xu et al., 2014; Lin et al., 2015), and includes extensively distributed sand bodies (Wang et al., 2008, 2010; Tan et al., 2011; Guo et al., 2013b; Zhao et al., 2015). In addition, the high ratio of sandstone thickness to total strata thickness has resulted in the mapping of uniform depositional facies over broad areas (Shi and Yang, 2011). However, such mapping cannot explain the marked heterogeneity giving rise to reservoir sweet spots; also it is not capable of enabling precise descriptions of deposits and reservoirs in the development stage. Thus, the present study is of value not only in terms of perspectives and methods, but also in the direct application to exploration and development in the study area.

2. Principles and methods

To explore new methods of lithofacies paleogeography mapping of large-area sand-rich strata, this study examined shallow braided river delta sediments in the Kimberley region of northwest Australia. These sediments constitute a typical modern large-area sand-rich deposit. Fig. 1 shows an aerial view of the delta during the dry season, when the channels are dry. As shown in Fig. 1, the braided river delta consists of several wide branching primary distributary channels that bifurcate upward into numerous small secondary distributary channels in highland areas on either side of the delta. These primary distributary channels are in low-lying areas and were subject to strong hydrodynamic flows during their deposition. In contrast, the secondary distributary channels are located in higher areas, and that deposition occurred under conditions of relatively weak hydrodynamic flow.

The observations above indicate that depositional characteristics vary from area to area based on geomorphological characteristics (Feng et al., 2015), which determine the depositional patterns of primary and secondary distributary channels (Fig. 2). During the initial stages of deposition, primary distributary channels in low-lying areas experience strong hydrodynamic conditions and are sites of the deposition of medium-coarse sands; grains are typically coarse in size and sediments are well sorted (Fig. 2a). As the base level rises, higher areas on either side of the channels experience weaker hydrodynamic conditions (during periods of flooding), and finer-grained sediments are deposited in secondary distributary channels, which are usually branches of primary distributary channels. In the highest areas, where hydrodynamic conditions are weakest, fine-grained inter-distributary silt-mud sediments are deposited (Fig. 2b). As the base level falls, the topography gradually becomes more level as a result of the deposition of sand bodies in the primary distributary channels in low-lying areas, and in secondary distributary channels in higher areas (Fig. 2c).

The above analysis indicates that a succession of geomorphological conditions can control depositional patterns and differentiate primary and secondary distributary channels on a braided river delta plain, and that sand bodies in distributary channels can be continually diverted and change course, with channels superimposed upon one another vertically, thus illustrating the evolutionary processes of deposition and the sedimentary characteristics of distributary channel systems. During the initial stage of

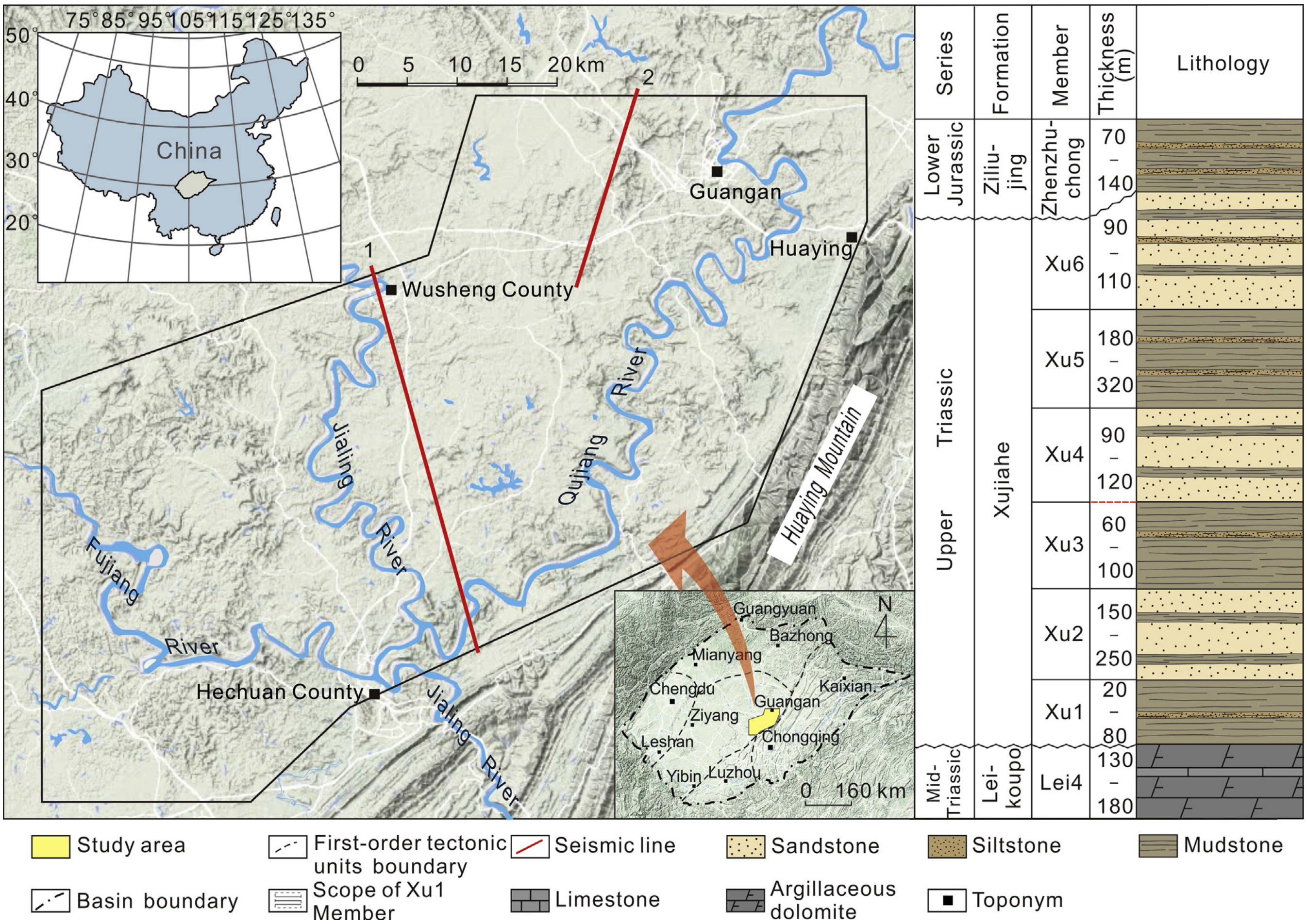

Figure 4. Regional structure of Sichuan Basin and geological overview of the study area.

deposition, the preexisting geomorphology exerts a marked controlling effect on deposition in primary distributary channels (Fig. 3a), as deposition occurs first in these channels in low-lying areas. As the base level rises, the primary distributary channels begin to change course and migrate to adjacent low-lying areas. As a result, areas of deposition expand and secondary distributary channels begin to develop in the relative high-lying paleogeomorphic areas (Fig. 3b). During later stages of deposition, as base level continues to rise, secondary distributary channels develop and are present in higher areas, and the control of the preexisting geomorphology on the pattern of primary and secondary distributary channels becomes stronger (Fig. 3c). In the final stages of deposition, multiple phases of sedimentation in distributary channels are superimposed upon one another; numerous primary distributary channels blanket low-lying areas, whereas the development of secondary distributary channels is concentrated in paleogeomorphic high-lying areas (Fig. 3d). Under conditions of constant deposition, the distribution of depositional microfacies on a given surface is characterized mainly by the pattern of primary distributary channels developed in an area, with the distribution of secondary distributary channels resulting in a patch-type distribution of deposits (Fig. 3e).

According to the above analysis, the development of primary distributary channels is concentrated in low-lying areas in the preexisting topographic surface, with deposition consisting of medium-coarse sandstone under strong hydrodynamic conditions; such conditions are suitable for the deposition of skeletal sand bodies and large sandstone sets. Therefore, this paper proposes a new method of lithofacies paleogeography mapping based on paleogeomorphic constraints, which adopts "sand bodies of primary distributary channels" instead of the commonly used "sandstone" as a single factor in the analysis, and uses the "ratio of sandstone to strata thickness" as a complementary single factor of the analysis. We propose a lithofacies paleogeography mapping method for revealing the distribution of skeletal sand bodies subject to paleogeomorphic constraints, according to the following principles.

(1) The paleogeomorphology of an area (prior to the deposition of sediment) is restored first, and the controlling effects of paleogeomorphology on the depositional patterns of strata are then analyzed;
(2) A sequence stratigraphic comparison is conducted for the entire area to establish the sequence stratigraphic framework. Then, map units are selected at time intervals appropriate for the particular study;
(3) The proper depositional units in the map area are selected as mapping factors; these units constitute the primary single factor. In the example of the shallow braided river delta described above, the sand bodies of the primary distributary channels are the primary single mapping factor. A contour map of the sandstone thicknesses of the primary distributary channels is developed by identifying the sand bodies based on the GR values, exploiting statistics related to the gross

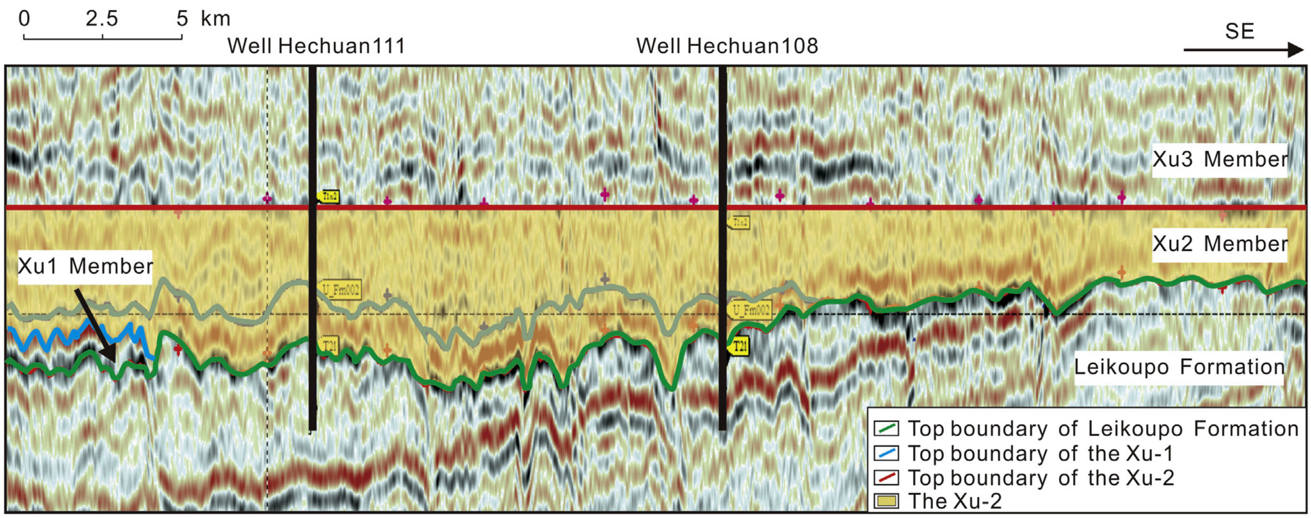

Figure 5. Seismic line section 1 (Fig. 4) showing the characteristics of filling and leveling of the Xu-2.

thickness of the sand bodies of primary distributary channels in each well in the study area, and considering the control of paleogeomorphology on the filling of the sand bodies;

(4) The dominant facies and microfacies are weighted by the thickness of each depositional unit at a given point, to establish the typical facies at each point. A correlation is established between each depositional microfacies and the primary single factor, and areas where different depositional microfacies are developed are identified in the primary single factor map;

(5) A lithofacies paleogeography map is constructed, and depositional microfacies in each well are checked and verified, in accordance with the dominant facies principle.

3. Geological setting

The Hechuan area is located in the middle of the Sichuan Basin, and the regional structure is part of the central uplift region (Fig. 4). Locally, the region is located on the slope of an uplift of upper Triassic foreland basin and the total area is 3.5×10^3 km^2. During the middle–late Triassic (200 Ma), the Paleo-Tethys Ocean gradually closed, and the Indo-China Block migrated towards the Yangtze Plate, subduction during this time caused sea level to fall (Liu et al., 2009). As the deposition of marine deposits on the passive continental margin basin of the Yangtze Plate ceased, a paraforeland basin stage ensued, starting in the early late Triassic (Chen and Ran, 1996) and triggered by compressional tectonics. The deposition of Xu-2 (equivalent to the Norian Stage of the late Triassic), which is examined in detail in the present study, marks the earliest basin-forming period in the foreland basin. At the same time, the eastern edge of the Songpan–Ganzi fold belt was folded, characterized by eastward-directed thrusting (Li et al., 1995), and a highland landform developed in the east and lowlands in the west.

The Hechuan area is underlain by marine strata dominated by carbonate rocks, and continental deposits dominated by sandstones of upper Triassic to Neogene age (Tong, 1992; Guo et al., 1996). The Xujiahe Formation consists of a series of terrigenous clastic rocks that include terrestrial, lacustrine, and fluvial facies. The thickness of the formation is relatively constant; the upper surface is a disconformable contact with the Zhenzhuchong Member of the Jurassic Ziliujing Formation, and the bottom surface is an unconformable contact with the underlying Leikoupo Formation. The Xujiahe Formation can be divided into six members (from bottom to top, Xu-1–Xu-6) based on rock associations and lithological characteristics. Xu-1, Xu-3, and Xu-5 are characterized by black shale, mudstone with thin layers of argillaceous siltstone, and coal seams; these members are the main hydrocarbon source layers and cap rocks in the Xujiahe Formation. Xu-2, Xu-4, and Xu-6 are characterized mainly by gray medium- to fine-grained lithic-arkose sandstone, arkose-lithic sandstone, and lithic-quartz sandstone; these members are the main reservoir beds in the Xujiahe Formation (Liu et al., 2005; Zhao et al., 2010).

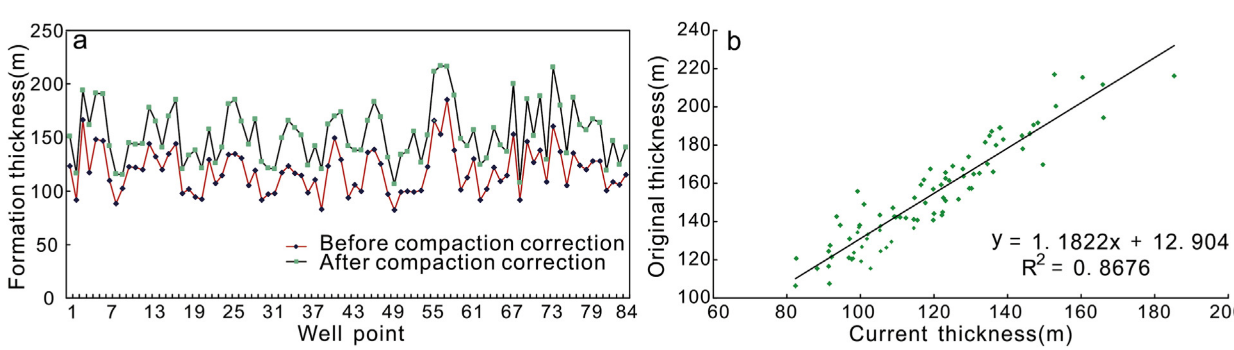

Figure 6. Gross formation thickness line chart (a) and scatter diagram (b) of the thickness before and after compaction correction of the Xu-1 and Xu-2 in the Hechuan area.

Please cite this article in press as: Zhong, Y., et al., Lithofacies paleogeography mapping and reservoir prediction in tight sandstone strata: A case study from central Sichuan Basin, China, Geoscience Frontiers (2016), http://dx.doi.org/10.1016/j.gsf.2016.09.002

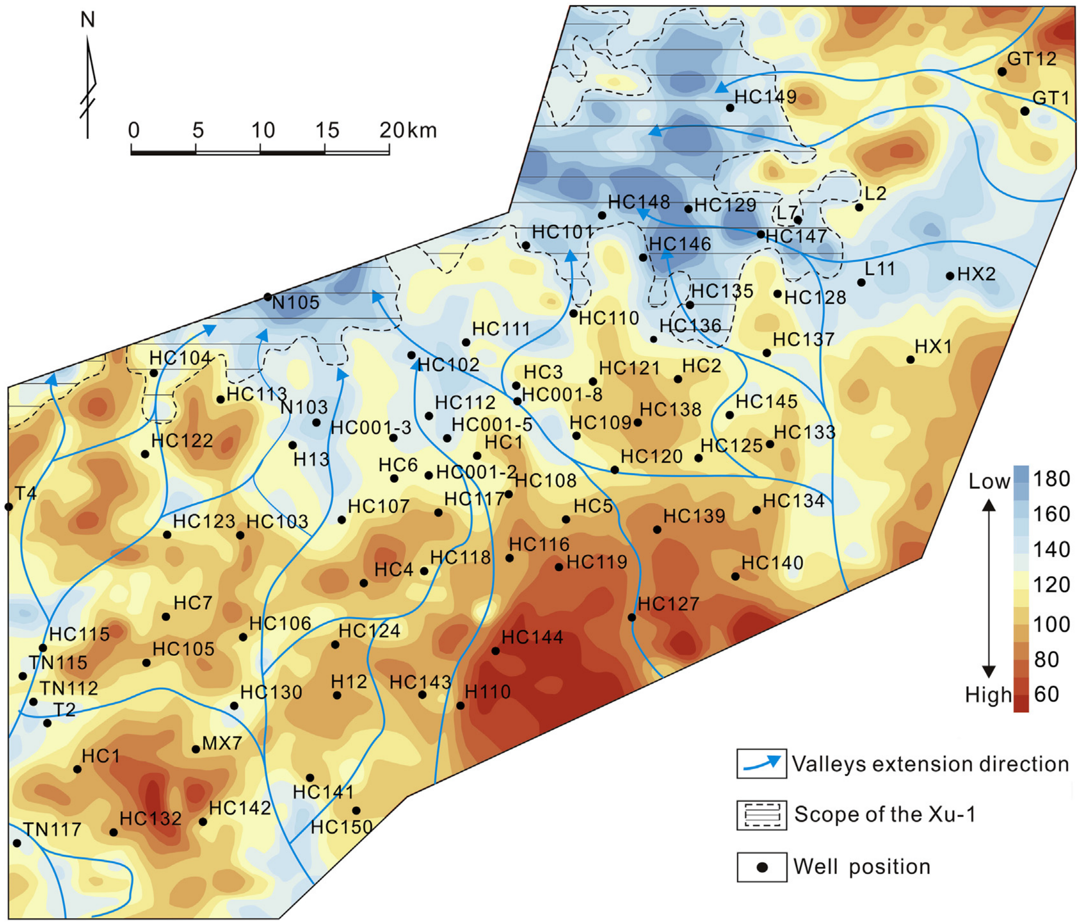

Figure 7. Paleogeomorphic features prior to deposition of the Xujiahe Formation in the Hechuan area.

The Xu-2 in the Hechuan area is composed of a set of terrigenous clasolite deposits, representing deposition in a warm, humid climate, and featuring large sets of sandstone in blocks containing thin black shale and coal deposits. The member is 150 to 250 m thick (Fig. 4) and in general is thicker in the west and thinner in the east.

4. Results

4.1. *Paleogeomorphological restoration and the sediment-filling characteristics of strata*

Numerous wells are present in the Hechuan area, but their uneven distribution hinders any detailed descriptions of the paleogeomorphology of the Xujiahe Formation during different depositional stages, as determined from thicknesses of drilled strata. The Xu-2 represents the filling and leveling of a karst surface on top of the Leikoupo Formation. The Xu-3 represents intrabasinal argillaceous lake-flooding deposits, which indicate that the top of the Xu-2 is relatively isochronous (Tan et al., 2013). Additionally, the top surfaces of the Leikoupo Formation and Xu-2 Member are easy to track in seismic sections (Fig. 5), which indicates that geophysical methods can be effectively used to measure thicknesses of strata between the top of the Leikoupo Formation and the top of the Xu-2; such thickness data are useful for detailed descriptions of karst paleotopography prior to deposition of the Xujiahe Formation. However, the Xu-1 and Xu-2 consist of sand and shale (with sandstone dominant), and the thickness ratio of sandstone to total strata differs among wells in the area, which can result in significant differences between the original and present-day thicknesses of strata. Moreover, thickness ratios of sandstone to strata in interwell areas, which are required for the seismic stratigraphy thickness method, are difficult to obtain, which also poses challenges for restoring the original thicknesses of the strata. Because of this, the gross thicknesses of the Xu-1 and Xu-2 are based on a large number ($n = 84$) of vertical wells. By considering the compaction rate of the Xujiahe Formation, the original formation thicknesses in the 84 vertical wells were restored using a compaction simulation method, as proposed by Guan (1992). The analysis demonstrates a significant linear correlation between present-day formation thickness and the restored original formation thickness (Fig. 6), indicating that in this area, variations in trends of present-day formation thickness approximate those of the original formation thickness. Thus, it is possible to approximately restore the karst paleogeomorphology prior to deposition of the Xujiahe Formation, using current formation thicknesses.

The current study is based on thickness variations in the Xujiahe Formation, as determined from the top of the Leikoupo Formation to the top of the Xu-2; these variations approximately represent the karst paleogeomorphology prior to deposition of the formation (Fig. 7). The paleogeomorphic map shows that prior to the deposition of the Xujiahe Formation, the topography was marked by a northwest-oriented overturn, moderately rugged terrain with noticeable concave-convex surfaces, and the development of

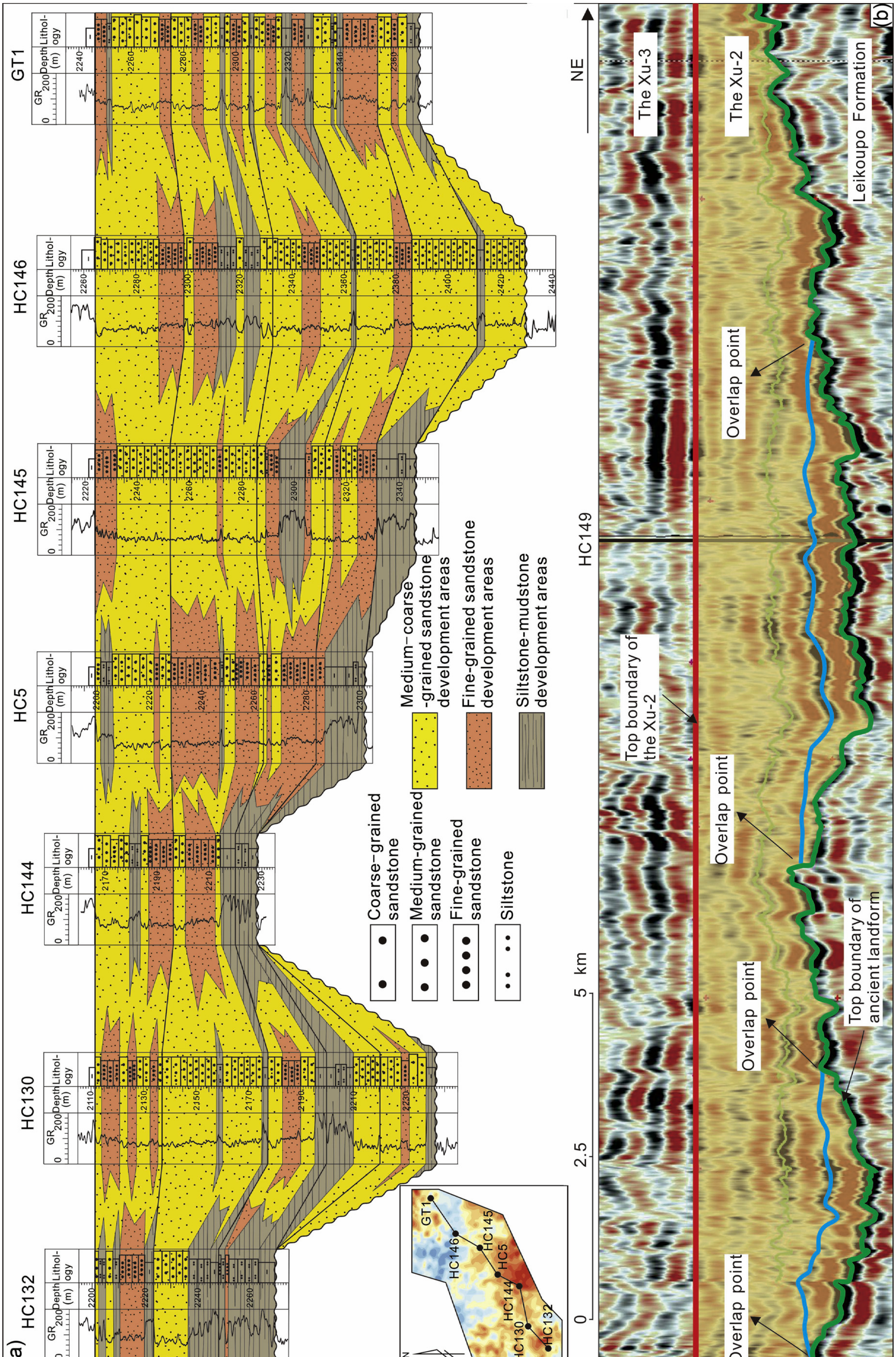

Figure 8. Paleogeomorphic control on the deposition of strata and the distribution of sand bodies along the crosscut valleys sections in the Hechuan area. (a) Coarse-grained sand deposits fill gullies, with deposits in high-lying areas to either side of the low-lying area becoming finer; (b) seismic line section 2 (refer to Fig. 4), showing that strata in valleys overlap highland areas on either side of the low-lying area.

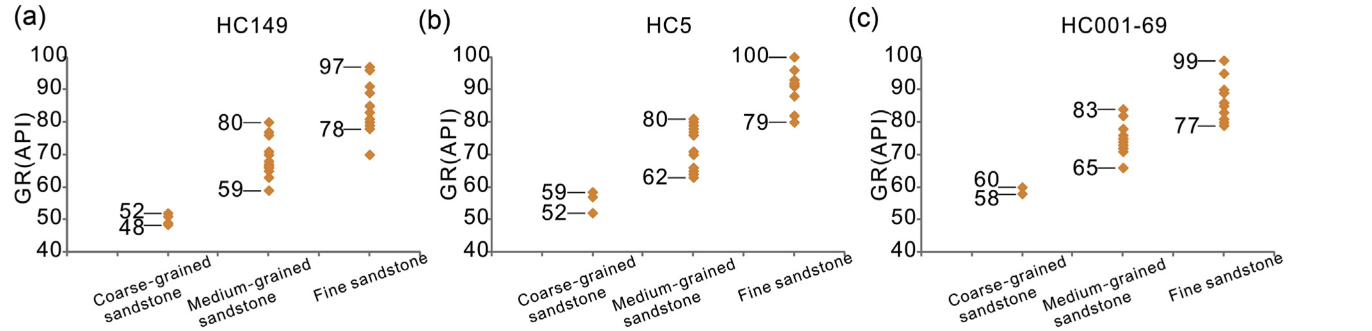

Figure 9. Statistical measures of the GR values of different sandstones in fully cored wells.

several valley systems extending northwestwards. The seismic data show that the Xu-1 is developed only in some topographically low-lying areas in the northwest, which indicates the influence of lacustrine environments on the deposition of this member. The Xu-1 is present only in the northwest of the study area, and Xu-1 deposits are absent in the remainder of the area (Fig. 7). Based on the paleogeographic location of the Hechuan area prior to late Triassic deposition (Tan et al., 2013), we suggest that the provenance area was mainly in the Jiangnan Ancient Land in the southeast of Sichuan basin.

The results of the paleogeomorphic restoration, with reference to the characteristics of formations, lithological correlation sections, and seismic sections crosscutting valleys, show that wells Hechuan 130 and 146 are located in a paleogeomorphic low area, and the well data show that in this area the formation generally consists of medium- and coarse-grained sandstone, with medium sandstone dominating. These features indicate that hydrodynamic forces were generally strong during deposition of the sand bodies in the Xu-2. The proportions of fine sandstone and mudstone increase from well Hechuan 146 to the higher-lying well Hechuan 145 and well Guangtan 1, located on either side of the low-lying area, thus reflecting deposition of these finer-grained sediments under conditions of weaker hydrodynamic forces. In the highest paleogeomorphic areas (wells Hechuan 132 and 144), fine-grained deposits are dominant and consist mainly of siltstone-mudstone and fine sandstone, indicating that hydrodynamic forces were further reduced in these areas (Fig. 8a). In addition, an overlap of low-lying strata onto highland areas on either side of the lowland can be observed in the seismic section along the crosscut valley section (Fig. 8b). These features are comparable to depositional characteristics of the modern braided river delta discussed above. Microtopographic differences between different karst topographies can result in significant variations in the distribution and accumulation of sand bodies during initial depositional stages. Sediments are first deposited in paleogeomorphic low-lying areas and consist of coarse-grained sands deposited in primary distributary channels. The high-lying areas to either side of low-lying areas are characterized by sediments deposited in secondary distributary channels and interdistributary deposits, and are finer grained than deposits in the low-lying areas.

4.2. Identification of skeletal sand bodies using well logs

We have derived the statistics for natural gamma values of coarse, medium, and fine sandstones in three fully cored wells in the study area, namely in wells Hechuan 149, 5, and 001-69. In well

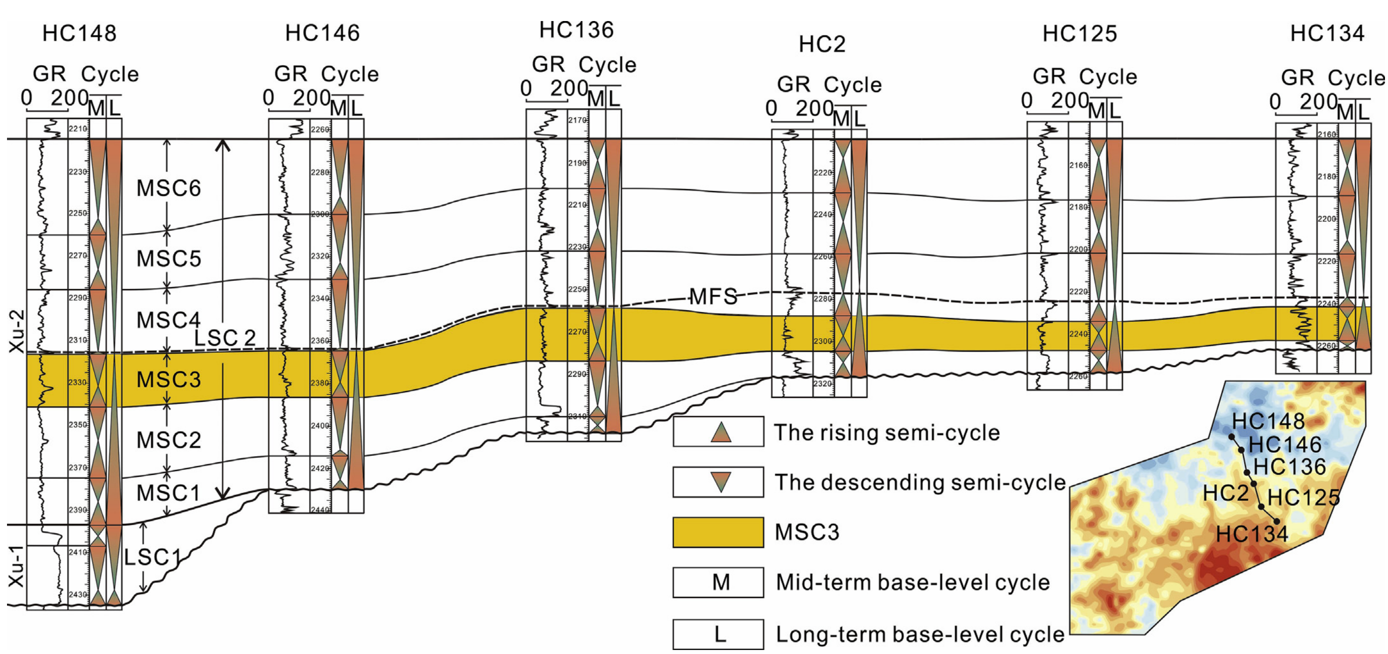

Figure 10. Comparison of sequences along a northwest–southeast transect for wells intersecting the Xu-2 in the Hechuan area.

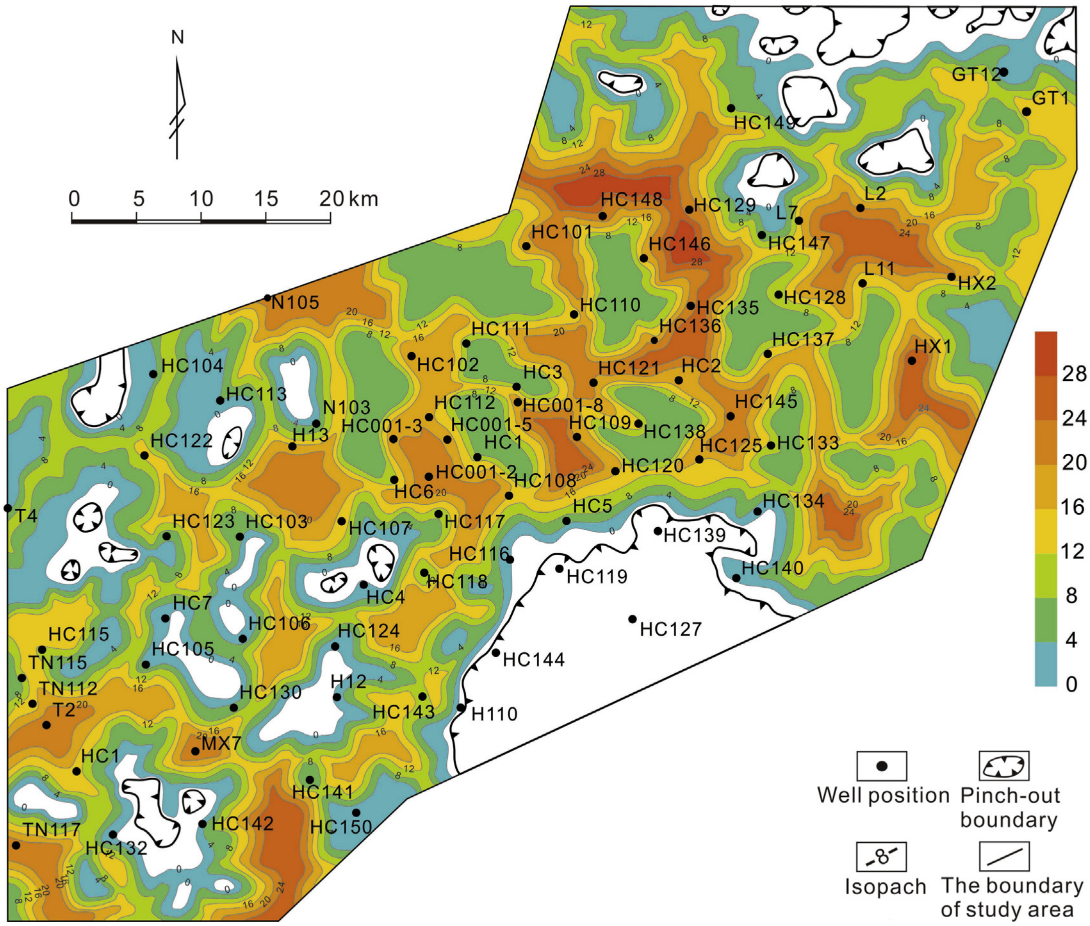

Figure 11. Contour map of the sandstone thickness of primary distributary channels in MSC3 of the Xu-2 in the Hechuan area.

Hechuan 149, GR values are 48–52 API in coarse-grained sandstone, 59–80 API in medium-grained sandstone, and 78–97 API in fine-grained sandstone (Fig. 9a). In well Hechuan 5, GR values are 52–59 API in coarse-grained sandstone, 62–80 API in medium-grained sandstone, and 79–100 API in fine-grained sandstone (Fig. 9b). In well Hechuan 001-69, GR values are 58–60 API in coarse-grained sandstone, 65–83 API in medium-grained sandstone, and 77–99 API in fine-grained sandstone (Fig. 9c). Based on these data, we consider that GR values of <60 represent coarse-grained sandstone, GR values of 60–80 represent medium-grained sandstone, and GR values of 80–100 represent fine-grained sandstone.

4.3. *Developing a sedimentary facies map of MSC3 in the Xu-2 using the new mapping method*

Based on the analysis of paleogeomorphic controls on sedimentation patterns, the Xu1 and Xu2 were assigned to two long-term base-level cycles, namely LSC1 and LSC2, respectively. LSC2 was further divided into six mid-term base-level cycles, namely

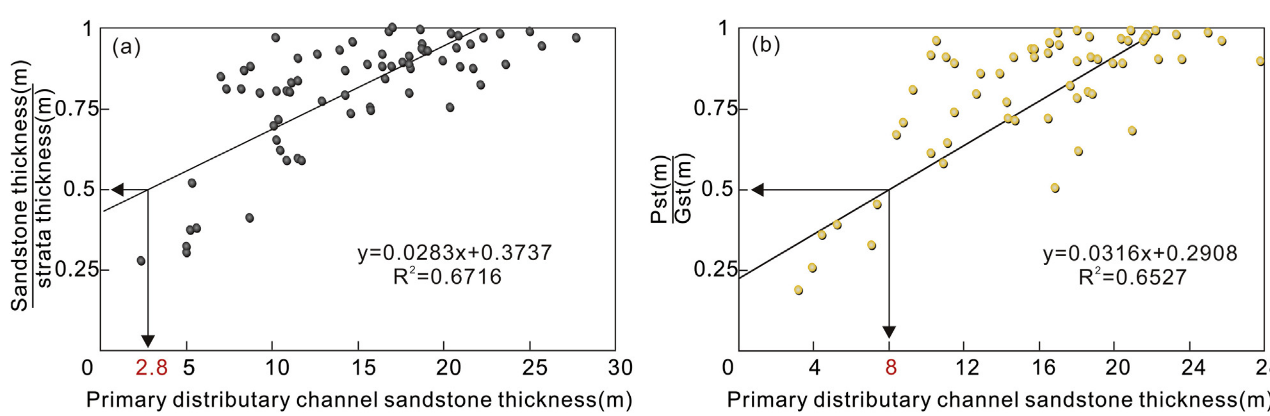

Figure 12. Correlation between each dominant facies and the thickness of primary distributary channel sandstone. Pst–Primary distributary channel sandstone thickness; Gst–Gross sandstone thickness.

Please cite this article in press as: Zhong, Y., et al., Lithofacies paleogeography mapping and reservoir prediction in tight sandstone strata: A case study from central Sichuan Basin, China, Geoscience Frontiers (2016), http://dx.doi.org/10.1016/j.gsf.2016.09.002

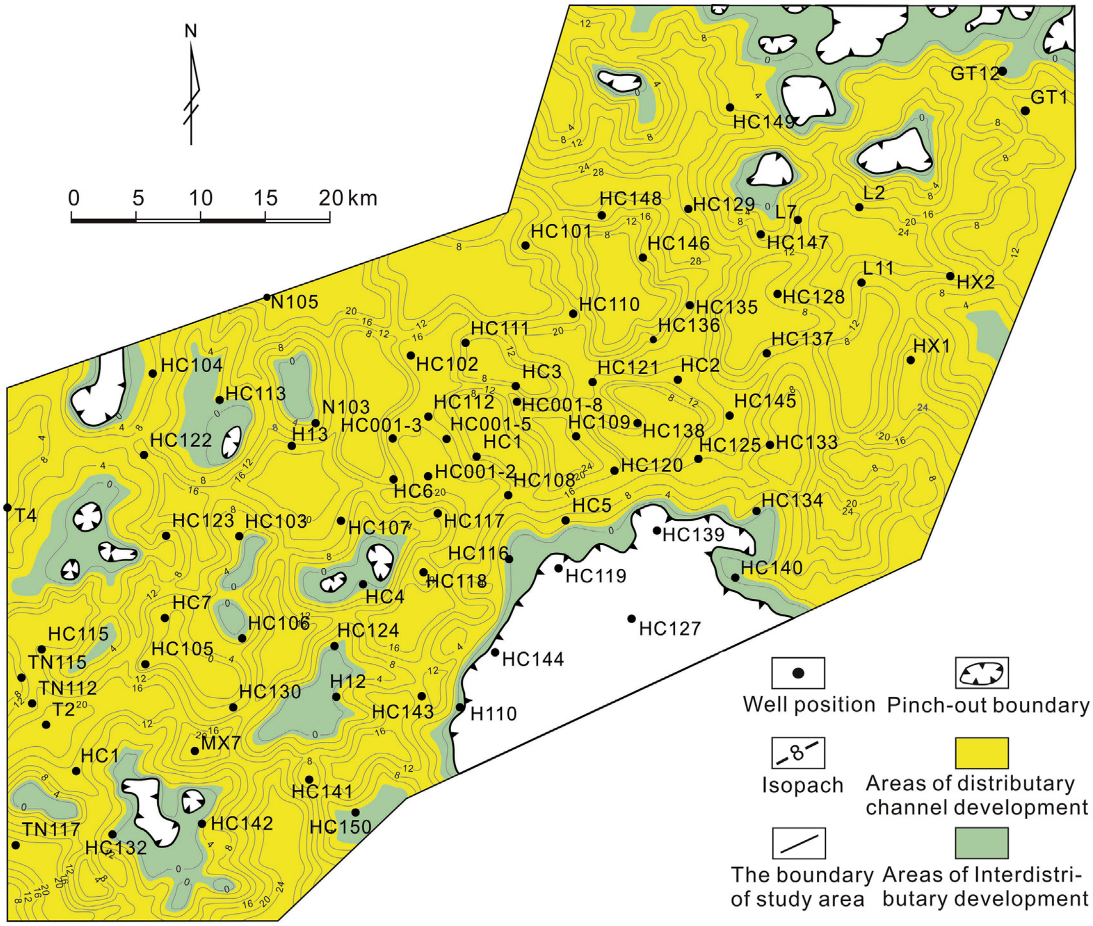

Figure 13. Areas of distributary channel and interdistributary development in MSC3 of the Xu-2 in the Hechuan area.

MSC1–MSC6 (Fig. 10). Considering the integrity of the sequence in the study area and the reliability of the available research data, cycle MSC3 was selected as an example of the application of the mapping method, as described below.

(1) To study the distribution pattern of sedimentary facies of the "sand-rich strata" in the Xu-2 in the Hechuan area, the Xu-2 was assigned to a long-term base-level cycle (LSC2) that included six mid-term base-level cycles. One of these cycles, MSC3, was used as the mapping unit;
(2) The depositional unit most appropriate for the mapping unit was selected as the primary single factor. The sand bodies of the primary distributary channels in MSC3 were selected as the primary mapping single factor, and a contour map of the sandstone thickness of primary distributary channels was developed by identifying the primary distributary channel sand bodies; i.e., those with GR values of <80 API, thus exploiting the statistics of the gross thickness of the primary distributary channel sandstones in each well, as well as considering the controls of paleogeomorphology on the distribution of sand bodies of primary distributary channels (Fig. 11);
(3) A dominant facies principle was employed, in which the depositional unit that accounts for the largest proportion of the total strata thickness is used to represent the sedimentary facies type at a given point. Given that the sandstone in the area generally consists of sand bodies deposited in braided river-delta-plain distributary channels, the ratio of sandstone thickness to total strata thickness can be used to determine if the distributary channel is the dominant facies or not at a given point; ratios of >0.5 indicate that distributary channels are the dominant facies. A linear relationship between the "ratio of sandstone to strata thickness" and "thickness of primary distributary channel sandstones" (Fig. 12a) shows a significant positive correlation between the two variables. The primary distributary channel sandstone thickness of 2.8 m, which corresponds to a ratio of sandstone to strata thickness of 0.5, was taken as the critical value. When the primary distributary channel sandstone thickness exceeds 2.8 m, the distributary channel microfacies are determined as the dominant facies. On the contour map of the sandstone thickness of primary distributary channels in MSC3, the value of 2.8 m was rounded up to a value of 3 m. The areas with sandstone thicknesses of >3 m were identified as areas of distributary channel development, whereas areas with thicknesses of <3 m were identified as areas of non-development of such channels. As the non-development areas are located in paleogeomorphic high-lying areas, and feature mainly the development of fine-grained deposits such as mudstone or siltstone, the areas of distributary channel non-development are represented mainly by the development of interdistributary and washland deposits (Fig. 13).

To differentiate between primary and secondary distributary channels in areas where such channels are developed, a critical thickness value is required. According to the dominant facies

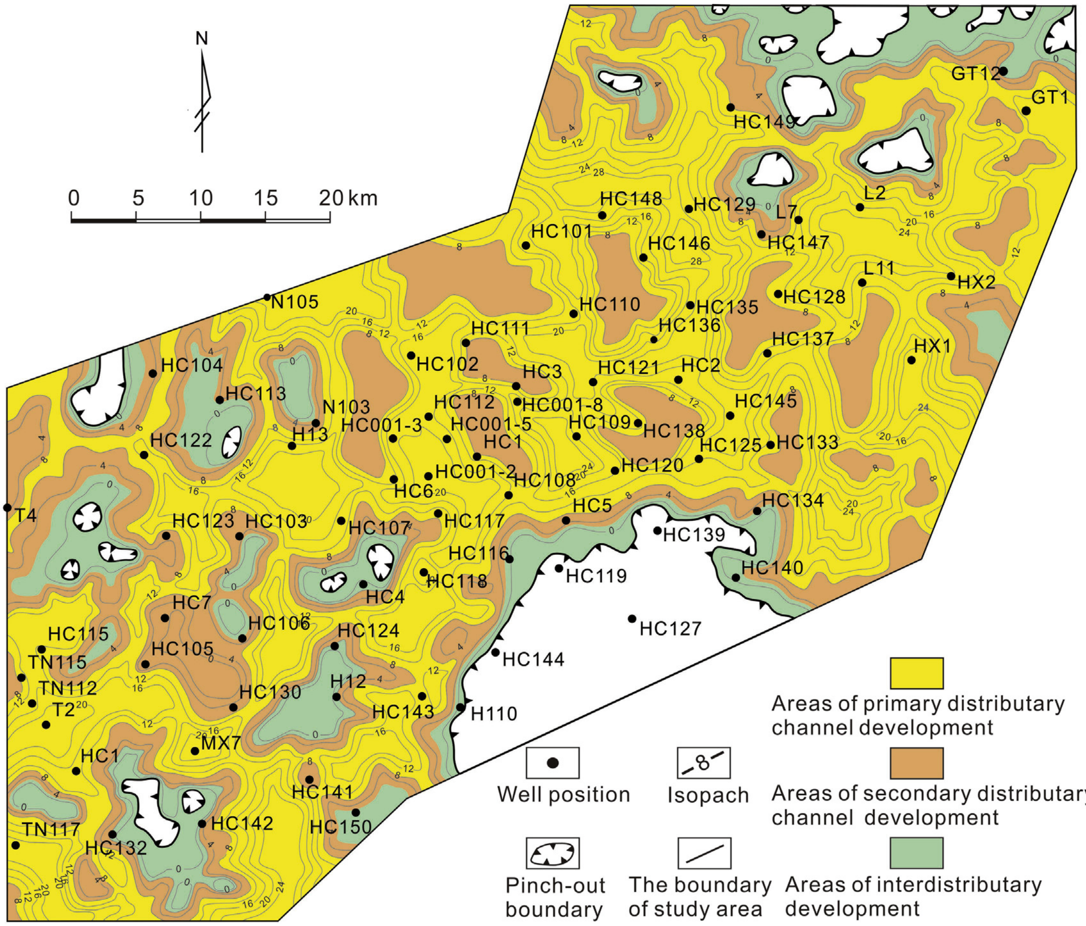

Figure 14. Sedimentary facies map of MSC3 of the Xu-2 in the Hechuan area.

principle, a critical value should be obtained from the scatter diagram of the relationship between the "primary distributary channel sandstone thickness/gross sandstone thickness ratio" and the "primary distributary channel sandstone thickness" (Fig. 12b). A sandstone thickness of primary distributary channels of 8 m corresponds to a ratio of primary distributary channel sandstone thickness to gross sandstone thickness of 0.5, and this value was used as the critical value to differentiate between primary and secondary distributary channels. On the contour map of the sandstone thickness of primary distributary channels, areas with thicknesses of >8 m are identified as areas of primary distributary channel development, whereas those areas with thicknesses of 3–8 m are identified as areas of secondary distributary channel development (Fig. 14). It can be seen from the figure that the areas of primary distributary channel development display good connectivity, whereas the areas of secondary distributary channel development scatter within the primary areas as patches.

5. Discussion

5.1. Effectiveness of the traditional method of mapping sedimentary facies

After developing a sedimentary facies map of MSC3 using the new mapping method, we compared it with the distribution of facies generated using the traditional method. The traditional method selects the "ratio of sandstone to strata thickness" as the primary single factor, with the areas with ratios of >0.5 being identified as areas of distributary channel development, and the areas with ratios of <0.5 being identified as interdistributary areas (Fig. 15). The areal distribution of distributary channels is large, however all the areas of distributary channel development are not favorable for reservoir development, Therefore, from the point of exploration and development, the accuracy of reservoir prediction using the traditional method is low.

5.2. Verification of reliability of the new method

The discovery of new reservoirs is an important criterion for checking the effectiveness of the proposed method for mapping sedimentary facies belts. A strong correlation between mapped facies belts and reservoir discoveries indicate that the sedimentary facies maps have important value for natural gas exploration. In fact, our compilation of statistics on reservoir thicknesses in the MSC3 layer in each well, and the construction of a bivariate plot showing the correlation between primary distributary channel sandstone thickness and reservoir thickness (Fig. 16), which indicates a strong positive correlation between the two. The results indicate that reservoirs should be better developed in areas where the dominant facies reflects the development of primary distributary channels.

Furthermore, by adding the thicknesses of MSC3 reservoirs obtained from each well to a sedimentary facies map in the form of a bar chart, it can be seen that reservoirs are better developed in

Please cite this article in press as: Zhong, Y., et al., Lithofacies paleogeography mapping and reservoir prediction in tight sandstone strata: A case study from central Sichuan Basin, China, Geoscience Frontiers (2016), http://dx.doi.org/10.1016/j.gsf.2016.09.002

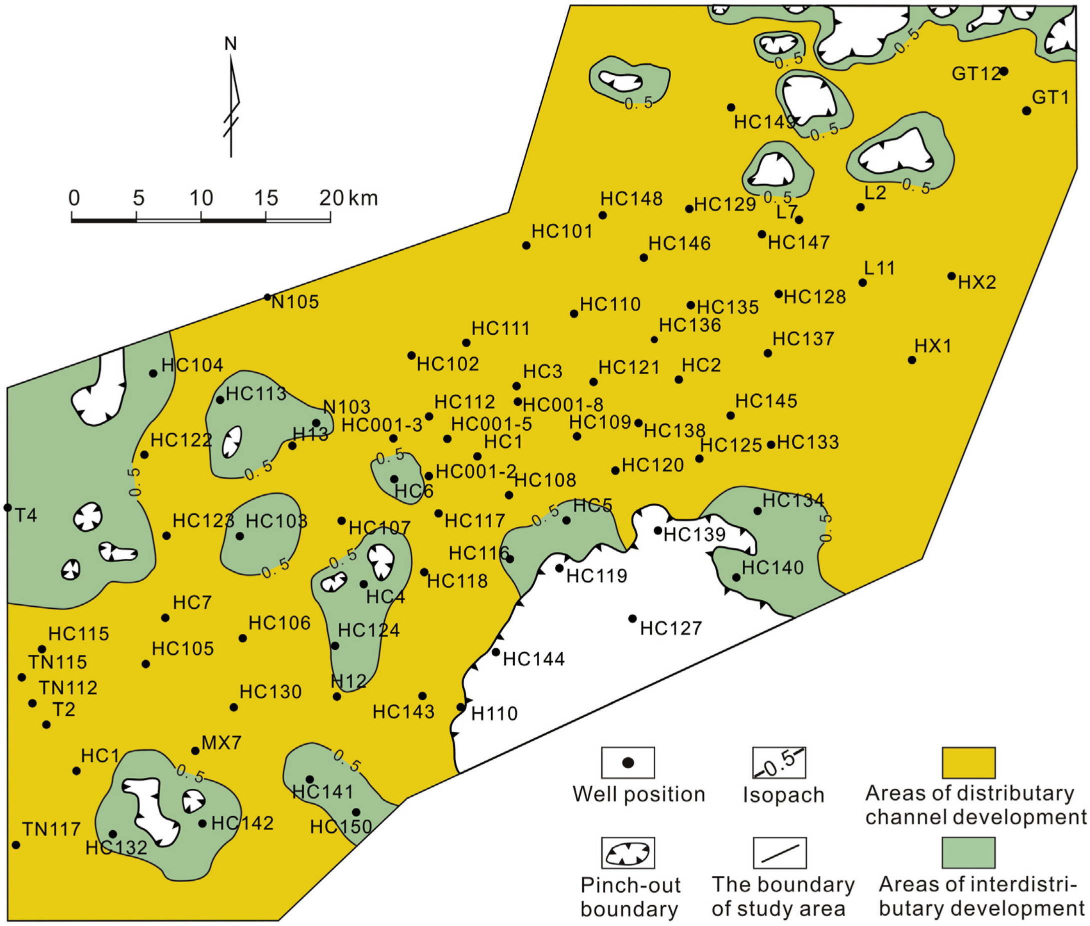

Figure 15. Sedimentary facies map of MSC3 of the Xu-2 in the Hechuan area using the traditional method.

areas of primary distributary channel development, and are more poorly developed or not developed in areas of interdistributary and secondary distributary channel development (Fig. 17). Also, by compiling statistics on reservoir thicknesses and formation porosity from each well in different facies belts, it was found that the porosities of formations in areas of primary distributary channel development (average, 9.06%) (Fig. 18a) were greater than those in areas of interdistributary and secondary distributary channel development (average, 3.29%) (Fig. 18b). Reservoirs are well developed in areas of primary distributary channel development (average thickness, 6.25 m) (Fig. 18c), but are poorly developed or not developed in areas of interdistributary and secondary distributary channel development (average thickness, 0.64 m) (Fig. 18d). From another perspective, these results demonstrate a significant positive correlation between areas of sedimentary facies development, the petrophysical properties of deposits, and the degree of reservoir development. The sedimentary facies map can therefore be used to predict favorable reservoir locations with a high degree of accuracy.

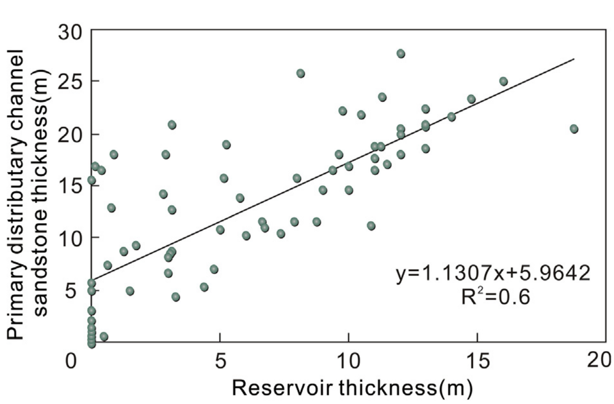

Figure 16. Correlation between the primary distributary channel sandstone thickness and reservoir thickness.

In general, lithofacies paleogeographic mapping of "sand-rich strata" enables identification of the primary single mapping factor. It also allows for the prediction of favorable reservoirs in widely distributed microfacies of distributary channels, which until now has proven difficult. The new method also establishes correlations between dominant facies and the primary single factor. It quantitatively calculates distribution trends and boundary locations for different microfacies. The method therefore provides reliable predictions of reservoir distributions.

6. Conclusions

(1) In this study, we analyzed the depositional characteristics of a modern braided river delta system in the Kimberley region, Australia, and established a depositional pattern and microfacies distribution model of primary and secondary distributary channels. The data were used to develop a lithofacies paleogeography mapping method based on the paleogeomorphic controls of topography on patterns of deposition.

Please cite this article in press as: Zhong, Y., et al., Lithofacies paleogeography mapping and reservoir prediction in tight sandstone strata: A case study from central Sichuan Basin, China, Geoscience Frontiers (2016), http://dx.doi.org/10.1016/j.gsf.2016.09.002

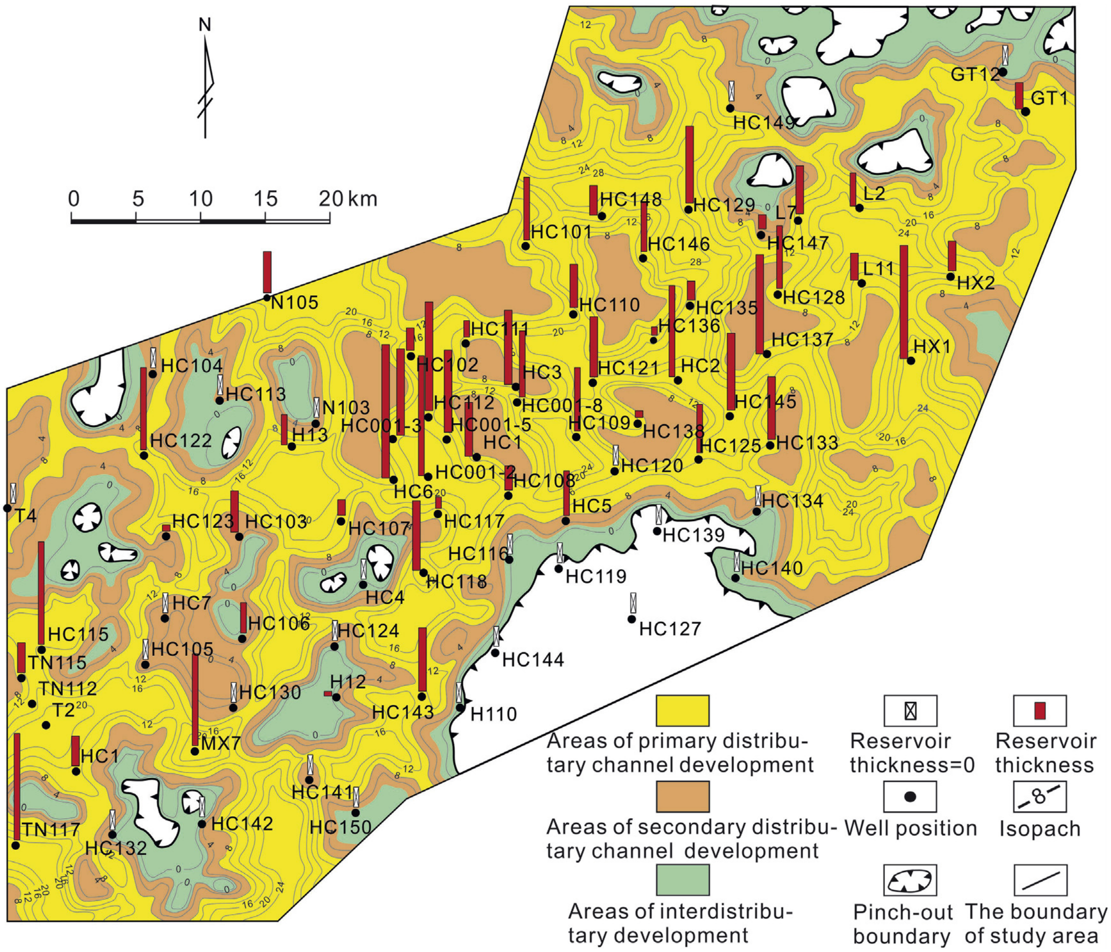

Figure 17. Comparison of reservoir development degree in different microfacies.

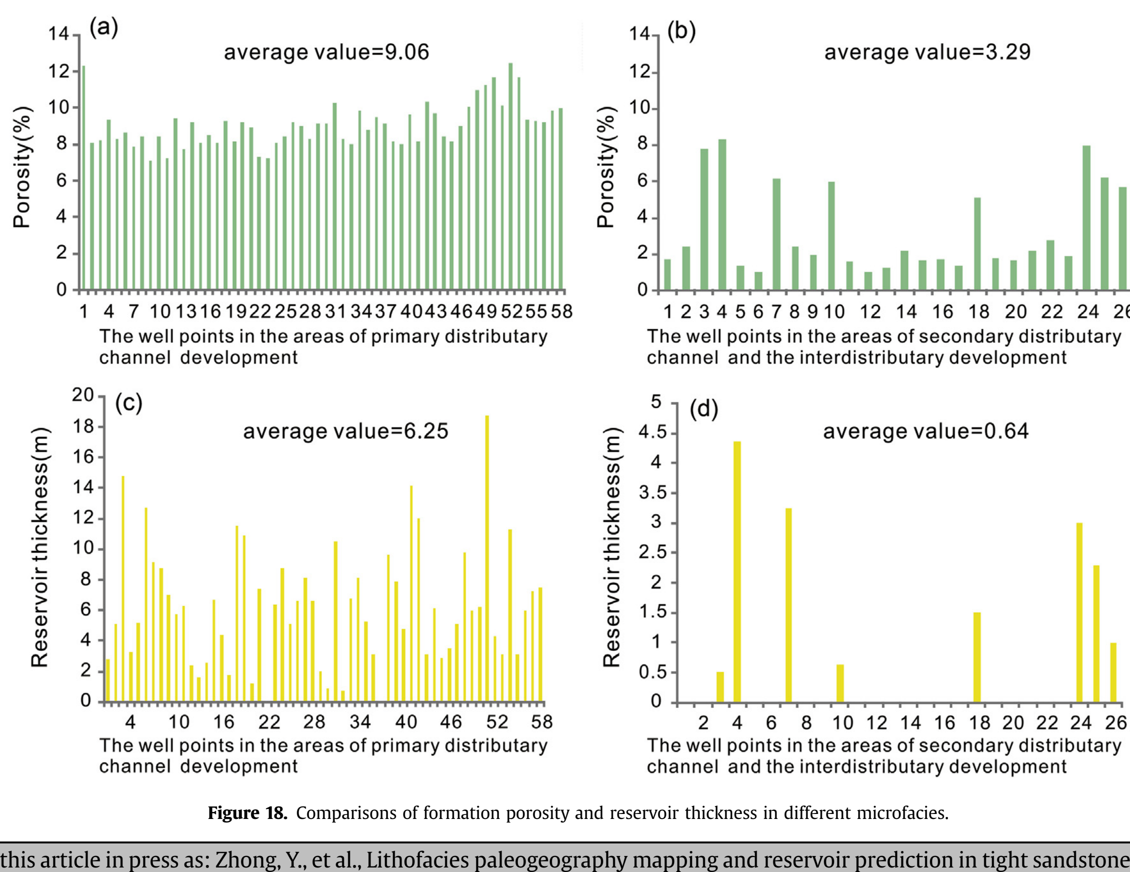

Figure 18. Comparisons of formation porosity and reservoir thickness in different microfacies.

(2) Taking the Xu-2 in the Hechuan area as an example, we could restore the paleogeomorphology prior to the deposition of the Xujiahe Formation by employing the impression method. In the well section along crosscut paleogeomorphic valleys, it can be seen that paleogeomorphology has a differentiation effect on the sediments in the sandstone. More specifically, in the lowest-lying paleogeomorphic areas with very strong hydrodynamic forces during deposition favour the development of medium (dominant) to coarse sandstones. Whereas at higher elevations the contents of fine sandstone increase due to weak hydrodynamic forces and the fine deposits consist of siltstone-mudstone and fine sandstone. In the seismic profile along the crosscut valleys section, it can be seen that deposits in paleogeomorphic low-lying areas overlap the high-lying areas to either side; this pattern is similar to that observed in the deposits of the modern braided river delta.

(3) The mapping method developed in this study is based on sequence division, using the mid-term cycle MSC3 in the Xu-2 as an example. The results show that extensively distributed planar sand bodies can be divided into areas of primary distributary channel development, secondary distributary channel development, and interdistributary channel development. The primary distributary channels are subject to paleogeomorphic controls and are interlaced with one another, with good connectivity. A significant correlation exists between the areas of different microfacies and the degree of reservoir development. Petrophysical properties are more favorable, and reservoirs are better developed, in areas of primary distributary channel development when compared to the areas of primary distributary channel non-development. This is the first report that convincingly correlates the depositional patterns with reservoir distributions in a gas field in the development stage.

Acknowledgments

This work was financially supported by the "13th Five-year" National Science and Technology major projects (No. 2016ZX05002006-005), the National Natural Science Foundation of China (No. 41502147), and the Sichuan Provincial University "non-conventional oil and gas" scientific research and innovation team construction plan. We thank Professor Jindong Xiao and Associate Professor Ling Li for their advice regarding this paper, and Dr. Di Xiao for comments on an earlier version of this manuscript.

References

Chen, F.J., Ran, L.H., 1996. Tectonic features and geodynamics of Mesozoic and Cenozoic foreland basins in China. Earth science–Journal of China University of Geosciences 21, 366–372 (in Chinese with English abstract).

Chen, S.Q., Wang, S.X., Zhang, Y.G., Ji, M., 2009. Reservoir prediction using pre–stack inverted elastic parameters. Applied Geophysics 6, 349–358.

Ding, X., Tian, J.C., Chen, J.S., Yao, J.L., Deng, X.Q., Li, Y.H., 2015. Paleogeographic framework and provenance features during Late Triassic Chang 9 time of the Yanchang Formation, Ordos Basin, China. Arabian Journal of Geosciences 8, 6731–6743.

Feng, D., Deng, H.W., Zhou, Z., Gao, X.P., Cui, L.T., 2015. Paleotopographic controls on facies development in various types of braid-delta depositional systems in lacustrine basins in China. Geoscience Frontiers 6, 579–591.

Gong, L., Zeng, L.B., Gao, Z.Y., Zhu, R.K., Zhang, B.J., 2015. Reservoir characterization and origin of tight gas sandstones in the upper Triassic Xujiahe Formation, Western Sichuan Basin, China. Journal of Petroleum Exploration and Production Technology 1–11.

Guan, Z.L., 1992. An attempt to calculate the primary thickness and the amount of differential compaction in a formation with an application of compaction simulations. Experimental Petroleum Geology 14, 152–158 (in Chinese with English abstract).

Guo, Y.C., Pang, X.Q., Chen, D.X., Yang, K.M., Jiang, Z.X., Zhang, X.P., Jiang, F.J., 2013a. Evaluation of upper Triassic T_3x^5 source rocks (western Sichuan depression, Sichuan Basin) and their hydrocarbon generation and expulsion characteristics: implication for tight-sand gas and shale gas accumulation potential assessment. Natural Resources Research 22, 163–177.

Guo, Y.C., Pang, X.Q., Li, J.H., Chen, D.X., Li, L.T., Zou, Y., Leng, J.G., 2013b. Evolution of uplift-depression framework in the middle western Sichuan depression and its control on hydrocarbon accumulation. Natural Gas Geoscience 24, 29–37 (in Chinese with English abstract).

Guo, Z.W., Deng, K.L., Han, Y.H., 1996. Formation and Evolution of Sichuan Basin. Geological Publishing House, Beijing (in Chinese).

He, F.B., You, J., Chen, K.Y., 2011. Gas sand distribution prediction by prestack elastic inversion based on rock physics modeling and analysis. Applied Geophysics 8, 197–205.

Khair, H.A., Cooke, D., Hand, M., 2013. The effect of present day in situ stresses and paleo-stresses on locating sweet spots in unconventional reservoirs, a case study from Moomba-Big Lake fields, Cooper Basin, South Australia. Journal of Petroleum Exploration and Production Technology 3, 207–221.

Li, Y., Zeng, Y.F., Yi, H.S., 1995. Sedimentary and Tectonic Evolution of the Longmenshan Foreland Basin,Western Sichuan, China. Press of Chengdu University of Science and Technology, Chengdu (in Chinese).

Lin, L.B., Yu, Y., Gao, J., Hao, Q., Huang, Q.S., 2015. Main controlling factors of Xujiahe Formation sandstone reservoir in South Sichuan, China. Journal of Chengdu University of Technoloy (Science & Technology Edition) 42, 400–409 (in Chinese with English abstract).

Liu, S., Zhang, H., Qu, G.S., Tang, J.M., 2009. Study on Structural Characteristics of the Thrust Fold of Longmenshan-Micangshan. University of Electronic Science and Technology of China Press, Chengdu (in Chinese).

Liu, S.G., Li, G.R., Li, J.C., Xu, G.S., Wang, G.Z., Xu, G.Q., Sun, W., Yong, Z.Q., 2005. Fluid cross formation flow and gas explosion accumulation in western Sichuan Foreland Basin, China. Acta Geologica Sinica 79, 5–8 (in Chinese with English abstract).

Liu, Z.F., 2014. Key techniques of integrated seismic reservoir characterization for tight oil & gas sands. Progress in Geophysics 29, 182–190 (in Chinese with English abstract).

Lü, Z.X., Ye, S.J., Yang, X., Li, R., Qing, Y.H., 2015. Quantification and timing of porosity evolution in tight sand gas reservoirs: an example from the Middle Jurassic Shaximiao Formation, western Sichuan, China. Petroleum Science 12, 207–217.

Masters, J.A., 1984. Elmworth. Case Study of a Deep Basin Gas Field. American Association of Petroleum Geologists, USA.

Mousavi, M.A., Bryant, S.L., 2012. Connectivity of pore Space as a control on two-phase flow properties of tight-gas sandstones. Transport in Porous Media 94, 537–554.

Poszytek, A., Suchan, J., 2016. A tight–gas reservoir in the basinal facies of the Upper Permian Ca1 in the southwestern Zechstein Basin, Poland. Facies 62, 1–13.

Prodanović, M., Bryant, S.L., Davis, J.S., 2013. Numerical simulation of diagenetic alteration and its effect on residual gas in tight gas sandstones. Transport in Porous Media 96, 39–62.

Shi, Z.S., Yang, W., 2011. Genesis of widespread sandbodies of upper Triassic in Sichuan Basin. Acta Sedimentologica Sinica 29, 1058–1068 (in Chinese with English abstract).

Shinn, Y.J., Lee, H.S., Kwon, Y.K., Kwak, W.J., 2014. Lithofacies distribution and depositional environment in the Lower Cretaceous McMurray Formation, BlackGold Lease, northern Alberta: implications for geometry and distribution of oil sand reservoirs. Geosciences Journal 18, 325–337.

Si, C.N., Wu, X.W., Xia, D.L., Wang, P., Zou, M., Xie, L.H., Liu, K.Y., 2015. The research of "sweet pot" prediction technology for tight sandstone reservoir—a case study of Chang3 reservoir of Yanchang Formation in Weibei Oilfield. Progress in Geophysics 30, 664–671 (in Chinese with English abstract).

Tan, X.C., Liu, H., Li, L., Luo, B., Liu, X.G., Mou, X.H., Nie, Y., Xi, W.Y., 2011. Primary intergranular pores in oolitic shoal reservoir of lower Triassic Feixianguan Formation, Sichuan Basin, Southwest China: fundamental for reservoir formation and retention diagenesis. Journal of Earth Science 22, 101–114.

Tan, X.C., Xia, Q.S., Chen, J.S., Li, L., Liu, H., Luo, B., Xia, J.W., Yang, J.J., 2013. Basin-scale sand deposition in the upper Triassic Xujiahe Formation of the Sichuan basin, Southwest China: sedimentary framework and conceptual model. Journal of Earth Science 24, 89–103.

Tong, C.G., 1992. Tectonic Evolution and Hydrocarbon Accumulation in Sichuan Basin. Geological Publishing House, Beijing (in Chinese).

Tong, X.G., Guo, B.C., Li, J.Z., Huang, F.X., 2012. Comparison study on accumulation & distribution of tight sandstone gas between China and the United States and its significance. Engineering Science 14, 9–15 (in Chinese with English abstract).

Wang, G.Z., Liu, S.G., Ma, Y.S., Xu, G.S., Cai, X.Y., 2010. Characteristics of subaerial karstification and late reconstruction in the Dengying Formation, Sichuan Baisn, southwestern China. Journal of Earth Science 21, 290–302.

Wang, Z.C., Zhao, W.Z., Li, Z.Y., Jiang, X.F., Li, J., 2008. Role of basement faults in gas accumulation of Xujiahe Formation, Sichuan Basin. Petroleum Exploration and Development 35, 541–547 (in Chinese with English abstract).

Wang, R.F., Song, H.Q., Tang, H.W., Wang, Y.H., John, K., Huang, G., 2016. Analytical modeling of gas production rate in tight channel sand formation and optimization of artificial fracture. Springerplus 5, 1–14.

Wei, G.Q., Yang, W., Jin, H., Xie, Z.Y., Shi, Z.S., Xie, W.R., Zhu, Q.Y., Liu, M.C., Li, D.J., Sheng, J.H., 2010. Distribution of favorable reservoirs and exploration targets in the upper Triassic of the Sichuan Basin. Natural Gas Industry 30, 11–14 (in Chinese with English abstract).

Xiao, L., Mao, Z.Q., Jin, Y., 2015. Tight gas sandstone reservoirs evaluation from nuclear magnetic resonance (NMR) logs: case studies. Arabian Journal Science and Engineering 40, 1223–1237.

Please cite this article in press as: Zhong, Y., et al., Lithofacies paleogeography mapping and reservoir prediction in tight sandstone strata: A case study from central Sichuan Basin, China, Geoscience Frontiers (2016), http://dx.doi.org/10.1016/j.gsf.2016.09.002

Xie, J.R., Zhang, J., Li, G.H., Tang, D.H., Peng, J., 2008. Exploration prospect and gas reservoir characteristics of Xujiahe Formation in Sichuan Basin. Journal of Southwest Petroleum University 30, 40–44 (in Chinese with English abstract).

Xu, Z.H., Hu, S.Y., Wang, Z.C., Wang, L., Bian, C.S., Zhong, B., Wu, Y.L., 2014. Characteristics and forming mechanism of large scaled sandstone reservoirs in Xujiahe Formation, Sichuan Basin, Southwest China. Natural Gas Geoscience 25, 1962–1974 (in Chinese with English Abstract).

Yang, H., Fu, J.H., Wang, D.X., 2004. Prediction of subtle thin gas reservoir in the loess desert area in the north of Ordos Basin. Applied Geophysics 1, 122–128.

Yang, R.Z., Zhao, Z.G., Peng, W.J., Gu, Y.B., Wang, Z.G., Zhuang, X.Q., 2013. Integrated application of 3D seismic and microseismic data in the development of tight gas reservoirs. Applied Geophysics 10, 157–169.

Ye, S.J., Lü, Z.X., Li, R., 2011. Petrophysical and capillary pressure properties of the upper Triassic Xujiahe Formation tight gas sandstones in western Sichuan, China. Petroleum Science 8, 34–42.

Yu, C.Q., Shao, J.Z., Wang, X.W., Zhang, X.M., 2010. The application of AVO technique to compact sandstone reservoirs in the Dingbei area of Ordos Basin. Progress in Geophysics 25, 1273–1279 (in Chinese with English abstract).

Zeng, Q.G., Gong, C.M., Li, J.L., Che, G.Q., Lin, J.P., 2009. Exploration achievements and potential analysis of gas reservoirs in the Xujiahe Formation, central Sichuan Basin. Natural Gas Industry 29, 13–18 (in Chinese with English abstract).

Zhao, W.Z., Wang, H.J., Xu, C.C., Bian, C.S., Wang, Z.C., Gao, X.H., 2010. Reservoir-forming mechanism and enrichment conditions of the extensive Xujiahe Formation gas reservoirs, central Sichuan Basin. Petroleum Exploration and Development 37, 146–157 (in Chinese with English abstract).

Zhao, Z.W., Li, L., Li, N., 2015. Identification of condensed section and its implication for exploration of tight sandstone gas: examples from Xujiahe 3 and Xujiahe 5 Members, Sichuan Basin. Natural Gas Exploration and Development 38, 10–12 (in Chinese with English abstract).

Zhou, L., Yuan, J.Y., Ren, D.Y., Zhang, J.L., Wu, Y., Zhou, Y.D., Song, J.C., 2015. Forecast on the advantageous area distribution of tight sandstone sweet spots reservoir in Sangonghe Formation Wenjisang area of Turpan-Hami Basin. Natural Gas Geoscience 26, 1003–1015 (in Chinese with English abstract).

Zhu, C., Guo, Q.X., Gong, Q.S., Liu, Z.G., Li, S.M., Huang, G.P., 2015. Prestack forward modeling of tight reservoirs based on the Xu–White model. Applied Geophysics 12, 421–431.

Zhu, R.K., Zou, C.N., Zhang, N., Wang, X.S., Cheng, R., Liu, L.H., Zhou, C.M., Song, L.H., 2008. Diagenetic fluids evolution and genetic mechanism of tight sandstone gas reservoirs in Upper Triassic Xujiahe Formation in Sichuan Basin, China. Science in China Series D: Earth Sciences 51, 1340–1353.

Zou, C.N., Tao, S.Z., Zhang, X.X., He, D.B., Zhou, C.M., Gao, X.H., 2009. Geologic characteristics, controlling factors and hydrocarbon accumulation mechanisms of China's Large Gas Provinces of low porosity and permeability. Science in China Series D: Earth Sciences 52, 1068–1090.