New directions in an established gas play: Promising dolomite reservoirs in the Middle Triassic Leikoupo Formation of the Sichuan Basin, China

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ABSTRACT

The discovery of carbonate gas fields in the Middle Triassic Leikoupo Formation of the Sichuan Basin has a complex history. In recent years, a series of structural fields have been discovered in the western Sichuan Basin. Their discovery confirms the immense exploration potential of the Leikoupo Formation. In this study, we analyze the characteristics of Leikoupo Formation exploration plays using exploration wells and test data, aiming to provide a reference for further discoveries. The Leikoupo Formation represents the uppermost unit in the Sichuan marine carbonate platform succession. During its deposition, the whole basin was characterized by a restricted and evaporitic platform. Two classes of reservoirs developed. One is pore–fracture reservoirs, in marginal platform and intraplatform shoals, and another is fracture–vug reservoirs in the karstic weathering crust of the formation-capping unconformity. Three hydrocarbon accumulation models were established for the Leikoupo Formation based on the spatial and temporal relationship among the source, reservoir, and cap rocks. Two types of exploration plays are present in the Leikoupo Formation, that is, shoal (including intraplatform shoal and marginal platform shoal) dolomite plays and karstic dolomite weathering crust plays (including intraplatform shoal karst and marginal platform shoal karst). The western Sichuan depression in the karstic slope belt presents immense exploration potential because of a proximal hydrocarbon supply, charging via an extensive fracture
network, shoals and karstic reservoir, a good seal rock of terrestrial mudstone, and potential composite hydrocarbon accumulations in stratigraphic traps, making it a promising area for future exploration.

INTRODUCTION

The Leikoupo Formation (247.2–242 Ma) is an assemblage of anhydrite-dominated evaporites and carbonates that represents the uppermost unit in the Sichuan carbonate platform succession (Lin and Chen, 2008; Li et al., 2012a; Zhu et al., 2014). Based on earlier exploration, the key to the discovery of oil and gas in the Leikoupo Formation is the location of the effective source rocks and the migration pathways connecting those source rocks with reservoirs (Wang et al., 1998; Liu et al., 2011; Feng et al., 2013; Liao et al., 2013). In recent years, exploration wells targeting the Leikoupo Formation made major hydrocarbon discoveries in the Xinchang–Jinma–Yazihe–Shiyangzhen structural belt along the western margin of the Sichuan Basin, with proven gas reserves greater than 3000·10^8 m^3 (10.5945 tcf).

The Leikoupo Formation has gradually become the primary exploration target in the western and central Sichuan Basin. Previous studies have suggested that additional promising reservoir intervals exist within the Leikoupo Formation, whereas organic-rich, lagoonal carbonates within the evaporitic platform of the Leikoupo Formation have excellent source rock potential (Feng et al., 2013; Xu et al., 2013; Huang, 2014; Xie, 2015). To promote sustainable exploration in the future, it is necessary to understand the hydrocarbon accumulation characteristics, especially the distribution and potential of favorable exploration plays.

In this study, the petroleum geology of the Leikoupo Formation is analyzed using well data available from the Sichuan Basin. Various exploration plays (White, 1980, 1988; Miller, 1982; Crovelli, 1987; Allen and Allen, 1990; Tong and He, 2001) were investigated with a focus on reservoir characteristics. Finally, favorable areas for further exploration were established based on a framework of spatial–temporal relationships among key hydrocarbon accumulation elements.

HISTORY OF PETROLEUM EXPLORATION IN THE LEIKOUPO FORMATION

Petroleum exploration of the Leikoupo Formation in the Sichuan Basin began in the 1970s. In December 1971, the Chuan 19 well in the Zhongba structure had a blowout in Member 1 of the Leikoupo Formation (Lei-1 Member, T2l1) and produced some light oil but was soon depleted. In November 1972, Member 3 of the Leikoupo Formation (Lei-3 Member, T2l3) in the Zhongba
area of the northwestern Sichuan Basin began to produce gas flow, indicating that the Leikoupo Formation is a substantial gas reservoir with reserves of $86.3 \times 10^8$ m$^3$ (304.8 BCF) (Zhu et al., 2011). Over the next 12 yr, numerous structures in the Leikoupo Formation of the western Sichuan Basin (e.g., Sumatou, Youguanding, Laoguanmiao, Daxing, Longfengchang, and Qinglinkou) were explored, but only water was produced (Zhai, 1989; Sun et al., 2017).

In December 1980, the Lei-1 Member gas reservoir was discovered in the Moshen 2 well, located in the Moxi structure of the central Sichuan Basin, but it was not put into production because of high sulfur content. In May 1987, the Lei-1 Member was confirmed to have proven reserves of $349.47 \times 10^8$ m$^3$ (1.2284 tcf), making it the principal pay zone of the Moxi gas field (Zhai, 1989). In the subsequent two decades, little progress has been made in the exploration of the Leikoupo Formation, except for the discovery of some small- to medium-sized gas fields: the Longnüsi and Luoduxi structures in the central Sichuan Basin, the Guanyinchang and Jieshichang structures in the southwestern Sichuan Basin, the Wolonghe structure in the eastern Sichuan Basin, and the Yuanba and Longgang structures in the northeastern Sichuan Basin (Figure 1).

From 2007 to 2012, two key exploration wells in the Xinchang structural belt, western Sichuan Basin (Chuanke 1 and Xinshen 1), produced high-yield commercial gas flow from the uppermost Leikoupo Formation, at rates of $86.8 \times 10^4$ m$^3$/day (30.65 MMCFGD) and $68 \times 10^4$ m$^3$/day (24.01 MMCFGD), respectively, of good source–reservoir conditions in the Leikoupo Formation (Song et al., 2013; Xu et al., 2013). In January 2014, a well located in the Jinma structure, in the southcentral part of the western Sichuan Basin (well Pengzhou 1), produced high-yield commercial gas flow from reservoirs in the upper Member 4 of the Leikoupo Formation (Lei-4 Member, T$_2$L4), below the unconformity capping the Leikoupo Formation, at the rate of $121.05 \times 10^4$ m$^3$/day (42.75 MMCFGD). This discovery marked a breakthrough in exploration of the marine successions of the Longmenshan piedmont structural belt. In July 2015, the Yashen 1 and Yangshen 1 wells in the Yazihe–Shiyangzhen structural belt also produced high-yield commercial gas flow from the Lei-4 Member, at rates of $48.5 \times 10^4$ and $60.32 \times 10^4$ m$^3$/day (17.13 and 20.30 MMCFGD), respectively, expanding the known extent of the Leikoupo Formation gas resource in the piedmont zone. So far, the proven reserves are greater than $3000 \times 10^8$ m$^3$ (10.5945 tcf), implying the potential for a series of future exploration plays.

**GEOLOGICAL SETTING**

The Sichuan Basin in the northwestern part of the Yangtze block is located adjacent to the Tethys ocean and the North China block. Its evolution was controlled by the Longmenshan intracontinental orogenic belt along the western margin and the Qinling orogenic zone along the northern margin (Guo et al., 1996; Meng et al., 2005). A series of major tectonic events, including the opening and closing of the South Qinling ocean basin (the northern branch of the paleo-Tethys ocean) (e.g., Ratschbacher et al., 2003; Nie et al., 2016), the opening and closing of the Ganzi–Litang, Jinshajiang, and Lancangjiang branches of the paleo-Tethys (e.g., Xu et al., 2015), and the opening and closing of the Neotethyan Yarlung–Zangbo River ocean basin (e.g., Aitchison et al., 2003), have formed a set of superimposed basins. They are composed, with time, of a passive continental margin succession during the Sinian to the Middle Triassic (Z–T$_2$), marine-to-continental rifted basin deposits during the deposition of Member 1 to Member 3 of the Xujiahe Formation of the Upper Triassic (T$_3$x$_1$–T$_3$x$_3$), intracontinental depression strata during the Member 4 of the Upper Triassic Xujiahe Formation to the Middle Jurassic (T$_3$x$_4$–J$_2$) and foreland basin deposits during the Late Jurassic to Quaternary (J$_3$–Q). The combined thickness of the Neoproterozoic–Middle Triassic marine succession and the Upper Triassic–Quaternary continental succession ranges from 6000 to 12,000 m (19,685 to 39,370 ft) (Wang, 2002; He et al., 2011). The Middle Triassic succession is separated into two distinct sedimentary facies zones by the Chengkou–Wanxian–Fuling belt. The predominantly clastic Badong Formation is present in the eastern area, whereas the carbonate-dominated Leikoupo Formation consists of the western part of the succession (Bureau of Geology and Mineral Resources of Sichuan, 1991). The Leikoupo Formation is distributed throughout the central and westcentral Sichuan Basin.
and represents the last unit deposition of carbonate in the Sichuan Basin. It pinches out to the south and east and thickens in the north and west (Bureau of Geology and Mineral Resources of Sichuan, 1991; Guo et al., 1996).

At the base of the Leikoupo Formation, green pisolites are widespread, with the thickness of 0.5–3 m (1.6–9.8 ft). The lithology transitions up-section into limestone, dolomite interbedded with anhydrite and other evaporites, breccias, sandstone, and mudstone, with slight lateral variation in lithology. Bivalves (Eumorphotis [Asoella], Myophoria [Costatoria] goldfussi) and ammonites (Progonoceratites pulcher) as well as foraminifera (Glomospira sp.) and conodonts (Neospathodus germanicus and Nicoraella kockeli) are present (Bureau of Geology and Mineral Resources of Sichuan, 1991; Guo et al., 1996). The Leikoupo Formation is divided into four members, numbered Lei-1 through Lei-4 vertically. To the west of the Longmenshan Mountains, the top of the Lei-4 Member transitions into the Tianjingshan Formation, which is a set of thick continental flysch
deposits containing effusive mafic to intermediate volcanic rocks. Carbonate gravity flow deposits (deposited along the margin of an ocean trough) are found in the transition zone along the western margin of the Yangtze block.

At the end of the Middle Triassic, the Indosinian movement led to broad tectonic uplift of the Sichuan Basin. As seawater regressed from the upper Yangtze platform and the Luzhou and Kaijiang paleo uplifts were formed, an approximately 10-m.y. depositional hiatus resulted. Consequently, Middle Triassic carbonates were widely eroded and karstified, with regional unconformities developed (An, 1962, 1996). The upper part of the Lei-4 Member in the western Sichuan depression was partially eroded, with the thickness of denudation decreasing from east to west (Figure 1). This period of exposure resulted in the formation of karst reservoirs in the uppermost Middle Triassic strata (Zhong et al., 2011; Tang, 2013; Ning et al., 2015). During the early stages of the Late Triassic, the western Sichuan Basin was compressed because of gradual closing of the paleo-Tethys ocean (Zhai et al., 2016). The Upper Triassic Maantang Formation (T3m) is believed to be correlative with the Member 1 of the Xujiahe Formation (T3x1), was deposited in a gently sloping marine ramp formed by the foreland flexure, and unconformably overlies the Leikoupo and Tianjingshan Formations (Liu et al., 2009a).

CHARACTERISTICS OF LEIKOUPO FORMATION RESERVOIRS

Lithology and Lithofacies

During deposition of the Leikoupo Formation, the Sichuan Basin was a partially enclosed epicontinental seaway with a paleotopographic high in the southeast and a low in the northwest (Feng et al., 1997; Liu and Tong, 2001). The majority of the Sichuan Basin was a rimmed, restricted, evaporitic platform (Lin and Chen, 2008; Li et al., 2012a, b; Lü et al., 2013). Laterally, beaded platform margin shoals occurred, along a northeast trend on the western margin of the Sichuan Basin. Lacustrine facies, gypsiferous lagoons, dolomitic flats, and shoal subfacies constitute the multiple sedimentary cycles. The Leikoupo Formation is 200–1200 m (656–3937 ft) thick, with the greatest thicknesses (generally >800 m (>2625 ft)) presented in the western Sichuan depression. The formation is generally divided into four members based on lithologic characteristics (Figure 2).

Lei-1 Member

The Lei-1 Member (T2l1) is dominated by thick anhydrite and anhydrite-dolomite strata, interbedded with silty dolomite, as well as minor halite and polyhalite. Its base is characterized by a succession of grayish-green to grayish-white illitic and siliceous mudstones, commonly known as green pisoliths (Bureau of Geology and Mineral Resources of Sichuan, 1997). During deposition of the Lei-1 Member, the Longmenshan–Yanyuan marginal basin existed to the west of the Longmenshan paleoisland chain, in a slope–bathyal environment; to the east were restricted evaporite platforms and marginal platform shoals, representing slight uplifts and sags (Figure 3A). Tidal flat and lagoonal carbonate rocks interbedded with evaporites accumulated in the platform interior. A succession of gray calcisparite dolosparite, limy dolarenite, arenaceous limy dolomite, light gray algal dolomite, oolitic dolomite, and dark gray dolomicrite is developed along the northwest margin of the Sichuan Basin, with individual grainstone packages with thicknesses of 8–30 m (26–98 ft), indicating deposition occurred in marginal platform shoals and intershoal environments. In the Yilong area, the Lei-1 Member gradually transitions into gypsiferous dolomitic flats; the depocenter is located near the Chuanke 1 well, where the member is approximately 240 m (~787 ft) thick. The Lei-1 Member thins to northeast and southwest (Figure 3A).

Lei-2 Member

The Lei-2 Member (T2l2) in the western Sichuan Basin can be subdivided into three sections (Xu et al., 2011). The lower section is composed of dark gray algal calcarenite, algal oncolitic dolomite, calcisparite, arenaceous oolitic dolomite, and oolitic limestone with interbeds of argillaceous dolomite. The middle section transitions upward from light gray algal-laminated dolomite and algal arenaceous dolomite to micritic dolomite and silty dolomite. The upper section is dominated by dark gray, finely crystalline dolosparite and algal-laminated dolomite with
dissolution bird’s-eye pores and geopetal structures. The depositional thickness of individual grainstone intervals ranges from 12 to 158 m (39 to 518 ft).

The total thickness of the Lei-2 Member in the Chuanke 1 well is 381 m (1250 ft), symmetrically decreasing to 80–120 m (262–394 ft) to the southwest and northeast. Deposition was centered around three local subbasins (Figure 3B). The first is centered in the Yilong–Dazhou–Nanchong area and has a total thickness of 100–200 m (328–656 ft). These strata consist of a lower interval of light gray dolomite with thick interbeds of evaporites and an upper interval composed of dark gray limestone and argillaceous limestone with thinner evaporite interbeds. The second is centered in the Santai–Chengdu area and has a thickness of 180–260 m (590–853 ft). Strata are composed of interbedded argillaceous dolomite, anhydrite–dolomite, and evaporites. The third is centered in the Leshan–Ziyang–Zigong area, with a thickness of 80–120 m (262–394 ft). It is characterized by massive argillaceous dolomite and argillaceous limestone strata, interbedded with evaporites. The Lei-2 Member depositional setting inherited the framework of uplifts and sags that characterized the

Figure 2. Generalized stratigraphy and source rocks in the Sichuan Basin (modified from Dai et al., 2009, 2012), with enlarged part showing the subdivision of the Middle Triassic Leikoupo Formation (Fm.). $R_o$ = vitrinite reflectance; TOC = total organic carbon.
period of Lei-1 Member deposition; with the gradual regression of seawater, an increasingly restricted and evaporitic platform resulted.

**Lei-3 Member**

The Lei-3 Member (T₃l₃), in the Dujiangyan–Hanwang–Guangyuan belt along the western and northwestern margins of the Sichuan Basin, is composed of gray calcisparite and doloarenite, arenaceous calcitic dolomite, light gray algal dolomite, oolitic dolomite, and light gray dolomicrite, with echinoid spine debris and ostracods. The thickness of individual grainstone packages is 45–155 m (148–509 ft), whereas that of oolitic and arenaceous shoals is greater than 90 m (295 ft). In the Qionglai–Yaan area, along the southwestern margin of the Sichuan Basin, the unit is mainly composed of dark gray argillaceous limestone, gray limestone, dolomite, anhydrite–dolomite with interbedded doloarenite, calcarenite, and algal dolomite. Grainstone packages are generally 14–80 m (46–262 ft) thick, whereas oolitic or arenaceous shoals have an average thickness of 40 m (131 ft). The largest transgression of the Middle Triassic occurred during deposition of the Lei-3 Member, when shallow marine organisms (such as ammonites and brachiopods) were abundant. Nodular limestones were deposited in a wide area of the platform margin. The depocenter shifted eastward, indicating migration of the intraplatform sag and changing of the regional tectonic environment (Figure 3C).

**Lei-4 Member**

The Lei-4 Member (T₄l₄) is eroded to varying degrees in the western Sichuan Basin (Tang, 2013). The contact with overlying Upper Triassic strata is mostly disconformable, but in the Yazihe, Dayuanbao, and Huangqianqiao areas it is conformably overlain by the Tianjingshan Formation. The residual Lei-4 Member in the western Sichuan depression is 350–380 m (1148–1247 ft) thick, with a lower interval consisting

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Figure 3. Sedimentary facies during deposition of members different of the Leikoupo Formation in the Sichuan Basin: (A) depositional environments of the Lei-1 Member, (B) depositional environments of the Lei-2 Member, (C) depositional environments of the Lei-3 Member, and (D) depositional environments of the Lei-4 Member.
of massive gray to white anhydrite with interbedded dolomicrite and an upper interval consisting of light gray anhydrite–dolomite and dolomicrite with crinoids and algal lamellae. The Lei-4 Member can be divided into three submembers based on lithological associations (Figure 4). The lower submember \((T_2L^4)\) is 180–200 m (591–656 ft) thick and is dominated by thick anhydrite strata interbedded with dark dolomicrite. It is well preserved in most parts of the western Sichuan Basin. The middle submember \((T_2L^5)\) is 70–80 m (230–262 ft) thick and consists mainly of interbedded anhydrite and dolomicrite; beds are of varying thickness and pinch out to the east. The upper submember \((T_2L^3)\) is 90–120 m (295–394 ft) thick, and it is lithologically dominated by dolomicrite and finely crystalline dolomite, limy dolomite to dolomitic limestone, and algal calcarenite. It is mainly located along the western margin of the Sichuan Basin and pinches out to the east (Figure 3D). The Longmenshan paleoisland chain had largely already formed by the time the Lei-4 Member was deposited; marginal platform shoals and intershoal sedimentary facies belts are present along the paleoisland front. With ongoing uplifting of the Luzhou and Kaijiang structures, denudation accelerated, whereas the basin became strongly evaporitic because of regression and the arid climate (Gong et al., 2015). Gypsiferous lake and gypsiferous lagoon deposits expanded as the depocenter of the gypsiferous lake migrated westward (Li et al., 2012b).

### Types of Leikoupo Formation Reservoirs and Their Properties

Two types of high-quality reservoirs were developed in the Leikoupo Formation, that is, shoal dolomite reservoirs and paleokarst weathering crust reservoirs. The shoal dolomite reservoirs include both marginal platform and intraplatform shoal pore–fracture reservoirs, characterized by the Lei-1 Member and Lei-3 Member gas reservoir in the Moxi and Zhongba areas. The paleokarst weathering crust reservoir includes the unconformity karst (a fracture–vug reservoir), commonly in association with a marginal platform or intraplatform shoal pore–fracture reservoir, characterized by the Lei-4 Member gas reservoir in the Longgang area and in the western Sichuan depression as representative examples. In general, the rock physical properties of the Leikoupo Formation reservoir are controlled by sedimentary microfacies, dolomitization, and dissolution (Wu et al., 2011; Song et al., 2013; Tang, 2013; Long et al., 2016).

### Shoal Pore–Fracture Reservoirs

The period of Leikoupo Formation deposition corresponds to an important interval of shoal formation in the upper Yangtze area. Marginal platform and intraplatform tidal flat shoals were developed in all Leikoupo members and can serve as hydrocarbon reservoirs (Shen et al., 2008; Wang et al., 2009; Li et al., 2011; Tan et al., 2014).

Intraplatform shoal reservoirs were developed in the Lei-1 through Lei-4 Members, although they are best developed in the Lei-1 Member (Ding et al., 2012). Commercial gas flow has been produced from the Lei-1 Member in many areas, with the Moxi structure gas field as the most typical example. The reservoirs are lithologically diverse and include micrite to powder–crystalline limestone and dolomite, fine powder–crystalline limestone and dolomite, doloarenite, calcisparite, oolitic dolomite, and dolomicrite. Based on the pore-space classification schemed by Choquette and Pray (1970), we further considered diagenesis and reservoir quality evolution and identified the reservoir space as mainly composed of intercrystalline pores as well as solution-enlarged intercrystalline, interparticle, and intraparticle pores.

Marginal platform shoal reservoirs were found in the Lei-2, Lei-3, and Lei-4 Members. Large and laterally continuous arenaceous shoals are distributed throughout the northern and western Sichuan Basin. A commercial gas reservoir in the Lei-3 Member was discovered in the Zhongba area of the northwestern Sichuan Basin, with reservoirs composed of doloarenite, algal-bound dolomite, powder–crystalline dolomite, oolitic dolomite, and argillaceous dolomite. Reservoir space consists chiefly of interparticle, intraparticle, and intercrystalline pores, fractures, and solution-enlarged pores and fractures, making it a pore and fracture–pore type reservoir.

The Lei-1-1 submember reservoir in the central Sichuan Basin is relatively continuous and correlatable from well to well. The reservoir is mainly developed in the middle part of the Lei-1-1 submember, with a cumulative thickness between 7 and 10 m (23 and 33 ft) (Figure 5). Tests were conducted
Figure 4. Section of sedimentary facies in the Lei-4 Member, in the western Sichuan depression (location of section is shown in Figure 1, AA'). AC = acoustic logging curves; GR = natural gamma-ray logging curves; RD = deep investigate double lateral resistivity logging curves; RS = shallow investigate double lateral resistivity logging curves.
Figure 5. Stratigraphic correlation of wells in the Lei-1-1 accumulation (Penglai 1, Penglai 6, Penglai 18, Penglai 9, Mo 15, Mo 45, and Mo 19), in the Moxi area of the central Sichuan Basin (location of section shown in Figure 1, BB’). AC = acoustic logging curves; CNL = compensated neutron logging curves; DEN = density logging curves; GR = natural gamma-ray logging curves; RT = true formation resistivity logging curves; RXO = flushed zone formation resistivity logging curves.
on core samples taken from dozens of wells in the central Sichuan Basin and show that the effective porosity ranges from 3% to 27.6%, averaging 5.35%. The fine to powder–fine crystalline dolomite and doloarenite lithofacies show the highest porosity, averaging 4.78% and 5.54%, respectively (Figure 6A). The Lei-1 Member reservoir in the central Sichuan Basin is generally characterized by moderate porosity and low permeability, with locally moderate to high porosity and permeability. According to evaluation criteria of carbonate reservoirs in Sichuan Basin (Table 1), it can be classified as a type II–III reservoir.

The Lei-3 Member reservoir, in the Zhongba area of the northwestern Sichuan Basin, was deposited in an intertidal–subtidal shoal environment, where doloarenite, algal stromatolitic dolomite, and algal-bound dolomite were developed. In these algal dolomites and doloarenite, clay content is less than 2%. Dissolved pores (pinholes) were developed in the Lei-3 Member dolomite grainstone reservoir, characterized by solution-enlarged interparticle, intraparticle, and intercrystalline pores. Greater than 90% of total porosity is from dissolution. These dissolution pores are most consistently developed 150–200 m (492–656 ft) below the upper surface of the Leikoupo Formation (Zeng et al., 2007). The Lei-3 Member gas reservoir has low to moderate reservoir capacity, with an effective porosity of 2.4%–6.5% (averaging 4.57%) (Figure 6B) and a permeability

Figure 6. Histograms of porosity frequency and average porosity of different rock types for the (A) Lei-1 Member intraplatform shoal reservoir in the Moxi area and (B) Lei-3 Member marginal platform shoal reservoir in the Zhongba area. Porosity data modified after Zeng et al. (2007) and Huang et al. (2014) and used with permission of the Journal of Paleogeography and the Journal of Southwest Petroleum University (Science and Technology Edition), respectively.
of 0.01–1 md. The doloarenite, algal-bound dolomite, powder–crystalline dolomite, and algal stromatolitic dolomite show the highest porosity, ranging from 2.16% to 3.6% (Figure 6B). This is mainly a shoal–pore reservoir and is classified as type III (Table 1), with a total thickness of 23–120 m (75–394 ft).

**Table 1.** Evaluation Criteria of Carbonate Reservoirs in the Sichuan Basin

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<th>Reservoir Quality</th>
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<th>III</th>
<th>IV</th>
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<tr>
<td>Porosity, %</td>
<td>&gt;10</td>
<td>10–5</td>
<td>5–2</td>
<td>&lt;2</td>
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<tr>
<td>Permeability, md</td>
<td>&gt;1.0</td>
<td>1–0.25</td>
<td>0.25–0.002</td>
<td>&lt;0.002</td>
</tr>
<tr>
<td>Throat midvalue, μm</td>
<td>&gt;1</td>
<td>1–0.2</td>
<td>0.2–0.024</td>
<td>&lt;0.024</td>
</tr>
<tr>
<td>Pore structure</td>
<td>Large pore–medium-coarse throat</td>
<td>Large pore–medium-coarse throat</td>
<td>Intermediate pore–fine throat</td>
<td>Micropore–microthroat</td>
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Unconformity Karst (Weathering Crust) Fracture–Vug Reservoirs

**Intraplatform Karstic Shoal Reservoirs**—The karst reservoirs in the uppermost Leikoupo Formation and the upper part of the Lei-4 Member are mainly composed of fine powder–crystalline dolomite, micritic algal calcarenite, dolomitic calcarenite, calcisparite, doloarenite, clumpy algal dolomicrite, and limy dolomite. Reservoir pore spaces are mainly composed of solution-enlarged interparticle, intercrystalline pores, vugs, and fractures. The karstic unconformity fracture–vug reservoir in the upper Leikoupo Formation (Lei-4 Member) is mainly located 0–9 m (0–30 ft) below the top of the formation, up to a maximum of 50 m (164 ft) below the top (Zhou et al., 2010). Its cumulative thickness is roughly 20–55 m (66–180 ft), with moderate reservoir properties and type II–III reservoirs dominant according to the evaluation criteria of carbonate reservoirs in the Sichuan Basin (Table 1). Microfacies and paleokarstification are the key factors controlling the formation of fracture–vug type reservoirs (Zhong et al., 2011; Ma et al., 2012; Xin et al., 2012; Yang et al., 2014).

The Lei-4 Member gas reservoirs in the Longgang area are dolomitic paleokarst reservoirs and are lithologically composed of dolomite grainstone, dolomicrite, and dolomitic breccia with minor clastic material. Reservoir space is mainly characterized by intercrystalline pores, dissolution pores, dissolution vugs, dissolution fractures, and structural fractures. Karstic reservoirs are most abundant in the Lei-4 Member, approximately 100 m (~328 ft) below the unconformity surface. These are mainly fracture–vug reservoirs, with type III reservoirs predominant (Table 1).

The porosity of the weathering crust dolomite reservoir in the Lei-4 Member of the Longgang area is mainly between 1% and 5%, with a maximum of 9.9% and an average value of 3.2%. Samples with a porosity greater than 3% account for 50% of total samples, whereas those with permeability greater than 0.1 md account for 41% of samples. On the whole, it is a low-porosity and medium-permeability reservoir, with porosity and permeability having an exponential relationship (Figure 7A).

**Marginal Platform Karstic Shoal Reservoirs**—Numerous exploration wells in the western Sichuan depression have encountered large-scale weathering crust reservoirs in the uppermost Lei-4 Member. These reservoirs formed via subaerial exposure of marginal shoal dolomites during uplifting associated with Indosinian movement and the subsequent weathering and dissolution of the upper Lei-4 Member (Figure 8) (Zeng et al., 2007; Xu et al., 2012; Feng et al., 2013; Song et al., 2013; Meng et al., 2015). These reservoirs are widely distributed throughout the western Sichuan Basin; they are extremely thick, with moderate to high reservoir properties, making them the main exploration target in the marine strata of the western Sichuan Basin.

Well data and thin section study indicate that the Leikoupo Formation reservoir is lithologically composed of dolomicrite (Figure 9A), stromatolitic powder–crystalline dolomite (Figures 9B, 10A, C, E), and algal
Doloarenite (Figure 10B). They display good continuity with cumulative thickness of 45–80 m (148–262 ft) (Figure 8). The reservoir spaces found within the karst are diverse, including solution-enlarged intercrystalline (Figure 10A), interparticle (Figure 10B), fenestral (Figure 10E) and moldic pores (Figure 10F), dissolution vugs (Figure 10C), structural fractures (Figure 10D), and dissolution fractures. Porosity has been enhanced through dissolution and dolomitization and dominated by dissolution vugs, dissolution pores, and dissolution fractures.

**Dissolution Vugs**
Dissolution vugs are mainly in the anhydrite–halite of the lower Lei-4 Member and in dolomitic grainstones.

Dissolution vugs are mainly in the anhydrite–halite of the lower Lei-4 Member and in dolomitic grainstones. The dolomitic calcarenites found in the Xinshen 1, Yashen 1, and Yangshen 1 wells are especially enriched in dissolution vugs, which form a dense honeycomb pattern (Figure 9). Statistical data show that the density of dissolution vugs in the upper part of the Lei-4 Member in the Xinshen 1 well ranges from 195 to 314 vugs per meter (59 to 96 vugs per foot). All vugs are small sizes (2 × 2 to 3 × 4 mm [0.079 × 0.079 to 0.118 × 0.157 in.]). They are of subround shape and partially filled with secondary calcite.

**Dissolution Pores**
Dissolution pores are common in these reservoirs, with typical diameters of 0.05–1.0 mm (0.002–0.039

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**Figure 7.** (A) Porosity and permeability of the Lei-4 Member intraplatform karstic shoal reservoir in the Longgang area, Sichuan Basin. (B) Porosity and permeability of the marginal platform karstic shoal reservoir in the uppermost Leikoupo Formation, in the western Sichuan depression.
Figure 8. Fine-scale stratigraphy and rock properties to evaluate the reservoir quality in the uppermost Leikoupo Formation (Lei-4-3 submember), in the Shiyangzhen–Jinma–Yazihe structural belt of the western Sichuan depression (section location shown in Figure 1, CC’). DF = dissolved fractures; DV = dissolved vugs; Intercry. P = intercrystalline pores; Interpar. P = interparticle pores; Interpar. RP = interparticle residual pores; Intrapar. P = intraparticle pores; F = fractures; FP = fenestral pores; MP = moldic pores; PEM = permeability (md); POR = porosity (%); SE-Intercry. P = solution-enlarged intercrystalline pores; SE-Interpar. P = solution-enlarged interparticle pores; SE-Intrapar. P = solution-enlarged intraparticle pores; SF = structural fractures; S. PEM = small core sample permeability (md); S. POR = small core sample porosity (%); T₂₄⁴ = Middle Triassic Lei-4-2 submember; T₂₅₃ = Middle Triassic Lei-4-3 submember.
solution-enlarged intercrystalline pores are mainly found in dolomite, whereas solution-enlarged interparticle pores are found in algal dolomitic calcarenites (and to some extent in other calcarenites) (Figure 8). Some of these dissolution pores are filled with calcite.

Fractures
Both structural fractures and dissolution fractures are well developed in these reservoirs, with typical densities of 13–26 fractures per m (4–8 fractures per ft). Dissolution fractures are generally 0.01–1.5 mm (0.0004–0.0591 in.) wide, whereas structural fractures are commonly 40–160 mm (1.575–6.299 in.) long, 0.2–1.2 mm (0.0079–0.0472 in.) wide, and continuous to semicontinuous. Some are partially filled with secondary calcite.

Detailed tests were conducted on 82 core samples, taken from 5 wells in the western Sichuan Basin. The results show that the reservoir porosity ranges from 0.26% to 20.04%, averaging 3.66%. The samples with porosity greater than 2% have an average porosity of 6.29%. The samples with a porosity less than 2% account for 49% of total samples, those with a porosity of 2%–5% account for 32% of samples, and those with porosity greater than or equal to 5% account for 19% of samples. The permeability ranges from 0.000 to 21.62 md, with a peak value of 0.002–0.25 md (Figure 7B), and is strongly heterogeneous. In Figure 7B, the porosity–permeability correlation is good in medium- to high-porosity intervals but poor in low-porosity intervals, although some samples are characterized by low porosity and high permeability. Pore and fracture–pore type reservoirs predominate in the Leikoupo Formation gas reservoir; type II–III reservoirs are most common, with local development of type I (Table 1) reservoirs in some intervals (Figure 8).

EXPLORATION PLAYS IN THE LEIKOUPO FORMATION

Source Rocks for Leikoupo Formation Gas Reservoirs

Gas source correlation analysis indicates that the gas in the Leikoupo Formation is mainly derived from carbonate source rocks (Figure 11A) (Wang et al., 2003; Feng et al., 2013; Liao et al., 2014) and argillaceous coal-bearing source rocks (Figure 11B) (Dai et al., 1998; Feng et al., 2013) in the upper Permian units, Middle Triassic Leikoupo Formation carbonate source rocks (Figure 11C) (Zhang et al., 2007; Luo and Tang, 2012; Xu et al., 2013; Huang, 2014; Xie, 2015; Yang, 2016), and the coal-bearing dark gray to black argillaceous source rocks in the Upper Triassic Xujiahe Formation (Figure 11D) (Wang et al., 1989; Zhou et al., 2015).

The upper Permian carbonate source rocks are 0–412 m (0–1352 ft) thick, average at approximately 100 m (~328 ft) in most of the Sichuan Basin (Tang et al., 2011). This interval thins (generally <50 m [<164 ft]) to the southwest part of the basin (Figure 11A) but thickens to the northeast where it is generally greater than 100 m (>328 ft). These source rocks contain abundant fossils and organic material, dominated by sapropelic organic matter. Residual total organic carbon (TOC) content is generally 0.12%–2.05%...
Figure 10. Thin sections showing reservoir characteristics and porosity types in the upper Lei-4 Member. (A) Solution-enlarged intercrystalline pores, powder–crystalline dolomite, the Qionglai 1 well, 4774 m (15,662 ft). (B) Solution-enlarged interparticle pores, doloarenite, the Xiaoshen 1 well, 5800 m (19,029 ft). (C) Dissolution vug, powder–crystalline dolomite, the Pengzhou 1 well, 5817.8–5817.85 m (19,087.3–19,087.4 ft). (D) Structural fractures, dissolution vugs, and bird’s-eye micrite with limy dolomite, calcite content of 15%, part of which is micrite or finely crystalline calcite with dissolution pores developed into bird’s-eye structures, the Pengzhou 1 well, 5824.86 m (19,110.4 ft). (E) Fenestral pores, stromatolitic texture, fine powder–crystalline dolomite, the Yangshen 1 well, 6222.12 m (20,413.8 ft). (F) Moldic pores (after anhydrite), fine powder–crystalline dolomite with anhydrite, the Yashen 1 well, 5785.56 m (18,981.5 ft).
with an average of approximately 0.99% and is least abundant in the central and southern Sichuan Basin (Liu et al., 2012). Organic matter is mainly type I–II\textsubscript{1} (Cai et al., 2003; Huang et al., 2014), presenting good hydrocarbon generation potential.

The coal-bearing argillaceous source interval in the upper Permian is generally greater than 20 m (>66 ft) thick, with a maximum value of 130 m (427 ft) in some locations (Figure 11B). These source rocks are abundantly fossiliferous and contain organic matter of mixed terrigenous and marine origin. Residual TOC of the black mudstones and carbonaceous shales is generally 1.0%–5.0% and 5.0%–25%, respectively, and dominated by type III organic matter, with vitrinite reflectance ($R_o$) ranges from 1.2% to 2.8% (Hu et al., 2013). Moreover, the coaly interval is approximately 1–4 m (~3–13 ft) in thickness with high TOC of 30.9%–73.6% (Wei et al., 2015) and $R_o$ of 1.9%–3.4% (Hu et al., 2013). So the upper Permian coal-bearing measures are highly mature to overmature in most parts of the basin (with the exception of areas along the margins), and gas generation is dominant.

Xu et al. (2013), Huang (2014), and Xie (2015) found that the algae-rich lagoonal carbonates deposited in evaporite platform environments are promising source rock potential. The Leikoupo Formation carbonate source rock interval ranges from 0 to 550 m (0 to 1804 ft) in thickness, commonly with a value of 250–350 m (820–1148 ft) (Figure 11C). It is thinnest (generally <100 m [<328 ft]) in the northern segment of the Longmenshan and around the Luzhou and Kaijiang paleouplifts and
almost completely eroded in part of the Luzhou paleouplift. In general, the source rock interval tends to thin toward its two flanks, away from the thick Qionglai–Santai–Dazhou area. Residual TOC ranges from 0.02% to 1.08% but is predominantly in the range of 0.4%-0.6% (Yang, 2016), showing a limited hydrocarbon potential.

The Upper Triassic Xujiahe Formation is a coal-bearing strata, which can be divided into six members (T3x1–T3x6). The Xu-1, Xu-2, and Xu-3 Members (T3x1, T3x3, and T3x5) contain a dark gray to black coal-bearing argillaceous source rock interval, with thickness of 50–1000 m (164–3281 ft) (Wang et al., 2013). In the western Sichuan Basin, this source interval is generally greater than 400 m (1312 ft) thick. In the central and northern Sichuan Basin, this argillaceous source rock interval ranges from 100 to 250 m (328 to 820 ft) in thickness (Figure 11D). The residual TOC of the T3x1, T3x3, and T3x5 intervals ranges from 0.5% to 9.7%, averaging 1.96% (Figure 2), and the kerogens in these rocks are mainly of types II and III (Dai et al., 2009). It is dominated by humic organic matter and predominantly generates gas, although oil generation occurs regionally. The values of R0 range from 0.72% to 2.10% (Dai et al., 2012; Hu et al., 2013), indicating that Upper Triassic organic matter is mature to overmature. These Upper Triassic source rocks and the underlying Leikoupo Formation reservoirs jointly constitute an upper source and lower preservation assemblage.

**Hydrocarbon Accumulation Models for Leikoupo Formation Reservoirs**

Based on the thermal maturation of source rocks and the distribution of source–reservoir–cap rock assemblages, three hydrocarbon accumulation models can be established for Leikoupo Formation reservoirs. These include a long-range upward migration and accumulation model with the upper Permian (P3l) as source rock and Lei-1-1 submember (T2l1) and Lei-3 Member (T2l3) as reservoir rocks; a self-sourced migration and accumulation model, with the Lei-1–Lei-4 Members (T2l1–4) as source rocks and Lei-4-3 submember (T2l43) as reservoir rock; and a vertical downward migration and accumulation model, with the Upper Triassic (T3x) as source rock and Lei-4-3 submember (T2l43) as reservoir rock.

**Model 1: Long-Range Upward Migration and Accumulation, with the Upper Permian as Source Rock and the Lei-1-1 Submember and Lei-3 Member as Reservoirs**

In 2012, the Penglai 18 well in the central Sichuan Basin encountered a high-quality porous reservoir in the Lei-1-1 submember and began to produce high-yield gas flow. This Moxi gas field has proven reserves of $392.15 \times 10^8$ m$^3$ (1.3849 tcf), and its discovery has great significance for future exploration of the Leikoupo Formation in the Sichuan Basin.

The Moxi structure is located at the center of a northeast-dipping slope in the central Sichuan Basin. It is a secondary anticlinal structure, which was formed during the Late Triassic and mainly developed during deposition of the Middle Jurassic Shaximiao Formation (Sun et al., 2009; Yuan et al., 2014). In the following Yanshan and Himalayan periods, the area inherited the Late Triassic paleotectonic framework. Having formed prior to the generation of abundant oil and gas, the Moxi–Longnûsi structural trap was a favorable environment for hydrocarbon accumulation (Sun et al., 2011). In the Lei-1-1 reservoir, the gas is derived from a highly mature mixed-gas source (Wang et al., 1998); this is likely to be coal-related gas derived from the upper Permian (Longtan Formation, P3l), as well as a secondary contribution from Leikoupo Formation source rocks. The reservoir is composed of dolomitic shoals, which connect with gas sources via fault systems. In the adjacent Longnûsi structure, no hydrocarbon accumulation was formed, because of lack of faults for hydrocarbon migration (Liu et al., 2009b). In summary, the Moxi gas field is a structural trap in a favorable facies belt (Figure 12A).

Additionally, the Zhongba gas accumulation, in the Lei-3 Member, has an original gas–water contact depth of 2871 m (9419 ft), a gas-bearing area of 13.4 km$^2$ (5.17 mi$^2$), and a gas column thickness of 372 m (1220 ft), with proven reserves of $86.3 \times 10^8$ m$^3$ (304.8 BCF). Gas from the Lei-3 Member reservoir is highly mature (Qin et al., 2007) and mainly derived from cracked oil generated in upper Permian carbonates and mudstones (Liao et al., 2013). The reservoir is mainly composed of dolomitic shoals. During deposition of the Lei-3 Member, the Zhongba area was a marginal platform environment, where algal and arenaceous shoals were widespread (Lin et al., 2007; Zeng et al., 2010). Algal debris, arenite, and fine powder–crystalline dolomite allow for the development of high-quality reservoirs.
Postdepositional dissolution resulted in relatively high porosity and permeability, and pinhole dolomite reservoirs are well developed. Reservoir space takes the form of intergranular pores, intragranular pores, interalgal pores, and intra-algal dissolved pores.

The Zhongba structure is located in the toe of a nappe in the northern segment of the Longmenshan Mountains (Zhu et al., 2011). Because of multiple stages of compression, thrusting, and folding, fracture systems are well developed in these strata. Faults and fractures severed as migration pathways for gas. The Zhongba structure formed prior to the latest stages of the Indosinian movement (He et al., 2002), and this inherited structural high created an anticlinal trap favorable for hydrocarbon accumulation. The Zhangming fault cutting the southeastern limb of the Zhongba anticline is an important factor in hydrocarbon migration (Luo and Tang, 2012). This pathway allows linkage between the Lei-3 Member reservoir and Permian source rocks, both of which are located in its hanging wall. It is a structural trap gas in a favorable facies belt (Figure 12B).

**Figure 12.** Stratigraphic sections of some typical Leikoupo Formation reservoirs in the Sichuan Basin. (A) Moxi gas pool, long-range upward migration and accumulation model, with upper Permian Longtan Formation (P3l) as the source rock and Middle Triassic Lei-1-1 submember (T2l1) as the reservoir. (B) Zhongba gas pool, long-range upward migration and accumulation model, with P3l as the source rock and Middle Triassic Lei-3 Member (T2l3) as the reservoir. (C) Shiyangzhen–Jinma–Yazihe gas pool, self-sourced migration and accumulation model, with Middle Triassic Lei-1–Lei-4 Members (T2l1-4) as the source rock and Middle Triassic Lei-4-3 submember (T2l4l3) as the reservoir. (D) Longgang (LG) gas pool, vertical downward migration and accumulation model, with Upper Triassic Xujiahe Formation (T3x) as the source rock and T2l4l3 as the reservoir. T1j = Lower Triassic Jialingjiang Formation; T2l1 = Middle Triassic Lei-1-2 submember; T2l2 = Middle Triassic Lei-2 Member; T2l3l1 = Middle Triassic Lei-3-1 submember; T2l3l2 = Middle Triassic Lei-3-2 submember; T2l4l1 = Middle Triassic Lei-4-1 submember; T2l4l2 = Middle Triassic Lei-4-2 submember; T3m = Upper Triassic Maantang Formation.
Hydrocarbon accumulation in the Moxi and Zhongba gas reservoir proves to be a lower source, upper reservoir model, although nearby source rocks may also contribute some hydrocarbons.

Model 2: Self-Sourced Migration and Accumulation, with the Lei-1–Lei-4 Members as Source Rocks and Lei-4-3 Submember as Reservoir

The Lei-4-3 submember gas reservoir in the western Sichuan depression is characterized by a proximal hydrocarbon supply, a fracture network facilitating charging, a combined shoal and karstic reservoir, and a seal in the form of terrigenous mudstones. Hydrocarbons accumulated in a stratigraphic trap. The natural gas is derived from mature to highly mature proximal source rocks (Figure 13), which are likely to be algae-rich lagoonal carbonates in the Middle Triassic evaporite platform (Xu et al., 2013; Huang, 2014; Xie, 2015). Any contribution from upper Permian source rocks would need fractures and/or faults for gas migration. However, no large-scale faults are developed in the Shiyangzhen–Jinma–Yazihe–Xinchang structural belt, and evaporates are present in the Middle to Lower Triassic. Therefore, we infer that the principal source rocks are within the Leikoupo Formation itself.

Karstic and fractured reservoirs and marginal platform shoal reservoirs are both developed in the upper Leikoupo Formation. The western Sichuan Basin is located at the top of the karstic Leikoupo weathering crust slope, and the unconformity capping the Leikoupo Formation is widespread. Deposition occurred in shallow water, and marginal platform shoal grainstones were abundant; reservoirs are mainly composed of doloarenite, algal doloarenite, calcisparite, and algal and bioclastic limestone. Reservoir spaces are mainly secondary dissolved vugs and dissolved fractures, with minor primary pores. The cumulative thickness of these reservoirs is 59–75 m (194–246 ft).

A fracture network approximately 75 km (~46.6 mi) long and 20 km (12 mi) wide strikes northeast along the top of the Leikoupo Formation in the central western Sichuan depression (Xu et al., 2013). The density of microfractures is 22.33 fractures per km² (57.83 fractures per mi²). This network was formed late in the period of Indosinian tectonism, and it extends upward into the Xiaotangzi Formation and downward into the middle part of the Lei-4 Member (Xu et al., 2013; Li et al., 2016). Large-scale relief exists on top of Leikoupo Formation, forming substantial structural and stratigraphic–lithologic traps; the top of Leikoupo trap covers a total area of 1198.2 km² (462.6 mi²).

The muddy shales of the Upper Triassic Maantang–Xiaotangzi Formation (cumulatively 30–350 m [98–1148 ft] thick) act as direct cap rocks in this system. The regional indirect cap rocks are the shales of the Upper Triassic Xujiahe Formation (the Xu-3 and Xu-5 Members) and the red shales in the Jurassic–Cretaceous succession (cumulatively 200–1600 m [656–5249 ft] thick). Note that the formation water is dominantly by CaCl₂ type (Zhu et al., 2011; Qin et al., 2018). Anhydrite and halite are developed in the Middle and Lower Triassic. Below this evaporite layer, which is the dominant detachment, only small-scale faults are present. In summary, hydrocarbon accumulation in the western Sichuan Basin proves to be the model where source rocks and reservoir rocks are by themselves. Underlying source rocks contribute hydrocarbons to stratigraphically higher reservoirs, where they accumulate in stratigraphic traps (Figure 12C).

Model 3: Vertical Downward Migration and Accumulation, with the Upper Triassic Xujiahe Formation as Source Rock and Lei-4-3 Submember as Reservoir

In 2008, the Longgang 22 well produced high-yield commercial gas flow from the Lei-4-3 submember, revealing the characteristics of the gas reservoir in the weathering crust of the Leikoupo Formation.

The carbon isotopic composition of Lei-4-3 Member natural gas in the Longgang area is consistent with oil type and mixed-source gas from highly mature sources; it is likely predominantly composed of mature to highly mature mixed source gas, mature coal measure originated gas, and high-maturity oil type gas (Zhou et al., 2015). Gas source correlation analysis indicates that it is likely generated mainly from source rocks in the Upper Triassic Xujiahe Formation (Zhou et al., 2015). Strata in the upper Lei-4 Member are eroded to varying degrees, and the karstic weathering crust acts as a favorable reservoir (Xin et al., 2012; Long et al., 2016). The natural gas flows downward along the surface
of the Indosinian depositional break and fault system; the composite migration pathway is composed of both faults and fractures. The Longgang structure is a buried local structural high in a generally low-relief area and forms a relatively small structural trap (Yang et al., 2014). The overlying Xujiahe mudstone provides good sealing capacity. Hydrocarbon accumulation in the Longgang gas reservoir generally proves to be the upper source, lower reservoir model. It is a stratigraphic trap, which formed because of

Figure 13. A summary diagram showing the thermal evolution of organic matter in source rocks and hydrocarbon accumulation events at the Chuanke 1 well in the western Sichuan depression. E-Q = Paleogene to Quaternary; J1 = Lower Jurassic; J2z = Lower Jurassic Ziliujing Formation; J2 = Middle Jurassic; J2s = Middle Jurassic Shaximiao Formation; J3 = Upper Jurassic; J3s = Upper Jurassic Suining Formation; J3p = Upper Jurassic Penglaizhen Formation; K2 = Cretaceous to Quaternary; K1 = Lower Cretaceous; K2 = Upper Cretaceous; Ro = vitrinite reflectance; T1 = Lower Triassic; T2 = Middle Triassic; T3 = Upper Triassic; T3x1 = Member 1 of the Upper Triassic Xujiahe Formation (Xu-1 Member); T3x2 = Member 2 of the Upper Triassic Xujiahe Formation (Xu-2 Member); T3x3 = Member 3 of the Upper Triassic Xujiahe Formation (Xu-3 Member); T3x4 = Member 4 of the Upper Triassic Xujiahe Formation (Xu-4 Member); T3x5 = Member 5 of the Upper Triassic Xujiahe Formation (Xu-5 Member).
Figure 14. Classification of Leikoupo Formation (Fm.) exploration plays in the Sichuan Basin.
variation in sedimentary facies and Indosinian-age erosion and pinchout (Figure 12D).

**Exploration Plays in the Leikoupo Formation**

Two types of exploration plays (each with two subdivisions) can be identified in the Leikoupo Formation of the Sichuan Basin (Figures 14–16).

**Shoal Dolomite Exploration Plays**

1. In intraplatform shoal dolomite exploration plays, mudstones and carbonates of the upper Permian act as source rocks (Figure 14). Reservoirs are type II–III, composed of Lei-1 Member micrite, powder–crystalline and fine powder–crystalline limestone and dolomite, doloarenite, calcisparite, and oolitic dolomite. The distribution of reservoirs is mainly controlled by dolomitization and earlier dissolution processes (Shen et al., 2008). Evaporites within the Leikoupo Formation are the direct cap rock, with the Upper Triassic Xujiahe Formation mudstones serving as an indirect cap rock, implying the presence of some thief zones. Anticlinal traps are predominant, and stratigraphic traps served as a secondary trapping type. This type of reservoir can form when a single shoal body is sufficiently thick or when multiple shoals are well connected vertically and laterally continuous. The key to the

**Figure 15.** Summary map of the Leikoupo Formation shoal dolomite play in the Sichuan Basin. Structural units are labeled as follows: in the western Sichuan depression, I₁ is the northern segment, I₂ is the central segment, and I₃ is the southern segment; in the central Sichuan uplift, II₁ is the northern segment, II₂ is the central segment, and II₃ is the southern segment; in the eastern Sichuan high and steep fold zone, III₁ is the northern high–steep structural belt, III₂ is the central high–steep structural belt, and III₃ is the southern folded structural belt. Mts. = Mountains.
development of these accumulations is the presence of faults, which establish linkages between source rocks and reservoirs. This kind of play is mainly developed in the central part of the central Sichuan uplift (Figure 15), represented by the Lei-1 Member gas reservoir in the Moxi area and the Lei-3 Member gas reservoir in the Guanyinchang area.

2. In marginal platform shoal dolomite exploration plays, upper Permian mudstones and carbonates are the primary source rocks, with a secondary contribution from the dark shales and coal of the Upper Triassic Xujiahe Formation. The reservoir is mainly composed of algal calcarenite and fine powder–crystalline dolomite in marginal platform facies. The shales of the Upper Triassic Maantang–Xiaotangzi Formation (50–450 m [164–1476 ft] thick) serve as a cap rock. Anticlinal traps are predominant, although stratigraphic traps are also factors. This type of play is mainly developed in the northern part of the western Sichuan depression, along its western margin, with the Lei-3 Member gas reservoir in the Zhongba area as a typical example (Figure 15).

Karstic Dolomite Weathering Crust Exploration Plays

1. In intraplatform shoal karstic exploration plays, the dark mudstones of the Upper Triassic Xujiahe
Formation serve as source rocks and seal, whereas the karstic dolomite weathering crust of the upper Lei-4 Member acts as the reservoir, controlled by the microscale morphology of the paleokarst surface. Stratigraphic traps are common, with subordinate anticlinal traps. These plays are mainly distributed throughout the northern segment of the central Sichuan uplift, represented by the Lei-4 Member gas reservoir in the Longgang area (Figure 16).

2. In marginal platform shoal karstic exploration plays, the source rocks are the algae-rich carbonates rock in the Leikoupo Formation. Weathering and karstification of marginal platform shoal grainstones produce high-quality reservoirs, with great thicknesses and good continuity. Reservoirs are sealed by shales from the overlying Maantang and Xiaotangzi Formations, as well as the mudstones of the Xujiahe Formation. The Longmenshan thrust belt, along the western margin of the basin, contains several buried structural highs (Meng et al., 2015), which along with the variety of lithofacies leads to the development of multiple types of traps. Stratigraphic, anticlinal, anticlinal–lithologic, and fault–stratigraphic traps are present. Gas reservoirs of this type are widely distributed along the western margin of the western Sichuan depression (Figure 16). These plays are the most important targets for future exploration since they have the potential to result in large-scale oil and gas accumulations.

DISCUSSION

We comprehensively analyzed the spatial relationship between source rocks, reservoirs, and cap rocks based on available data from exploration plays. Because of the Indosinian movement at the end of the Middle Triassic, the entire Sichuan Basin was uplifted and subaerially exposed (An, 1962; Mei, 2010). The uppermost Leikoupo Formation was extensively eroded and formed a weathering crust. Reservoirs in the western Sichuan depression are predominantly located in this karst slope belt (Xu et al., 2013), with combined systems of shoal and karst reservoirs. This arrangement is highly favorable for the development of high-quality reservoirs, and this area should be a major exploration target in the future (Figures 15, 16).

The Leikoupo Formation and several intervals of the underlying marine strata and the upper Xujiahe Formation have hydrocarbon generation potential. The multiple source rocks are cut and connected by the piedmont thrust faults. However, hydrocarbon charge to the Lei-4 reservoirs appears to be mainly from proximal sources such as the Lei-3 Member or the lower Xujiahe Formation, with long-distance migration from such units as the Permian being a secondary factor.

Furthermore, multiple folded anticlines (related to subsurface faults) are found in the piedmont belt of the western Sichuan Basin (Tong, 1990; Li et al., 2006), with high amplitudes favorable for hydrocarbon accumulation. The mudstone of the overlying Maantang–Xiaotangzi and Xujiahe Formations and the interlayer anhydrite and halite of the Leikoupo Formation provide good sealing capacity. The western Sichuan depression contains all of the elements for the formation of structural traps in favorable facies belts, as well as stratigraphic traps, resulting in excellent exploration potential.

CONCLUSIONS

1. Two types of high-quality reservoirs were developed in the Leikoupo Formation, controlled by lithologic associations, sedimentary microfacies, the karstification of paleosurfaces, and later structural reworking. The first type is marginal platform (or intraplatform) shoal pore–fracture reservoirs; the second is reservoirs combining a karstic weathering crust having fracture–vug porosity with a marginal platform (or intraplatform) shoal pore–fracture reservoir.

2. Three hydrocarbon accumulation models can be established for the Leikoupo Formation based on the spatial and temporal relationship among the source rock, reservoir, and cap rock. These include model 1 (long-range upward migration and accumulation, with $P_3$ as the source rock and $T_2l_1$ and $T_2l_3$ as the reservoir rock), model 2 (self-sourced migration and accumulation, with $T_2l_{1-4}$ as the source rock and $T_2l_3$ as the reservoir rock), and model 3 (vertical downward migration and accumulation, with $T_3x$ as the source rock and $T_2l_4$ as the reservoir rock).
3. Two types of exploration plays (with four subdivisions) can be established in the Leikoupo Formation reservoir of the Sichuan Basin: (1) shoal dolomite plays (including intraplatform shoals and marginal platform shoals) and (2) karstic dolomite plays (including intraplatform and marginal platform shoal karst plays).

4. The Leikoupo Formation has great potential for oil and gas exploration. The karstic dolomite weathering crust and the marginal platform (or intraplatform) shoals of the Leikoupo Formation in the western Sichuan Basin are favorable exploration targets.

REFERENCES CITED


Long, Y., S. G. Liu, J. M. Song, W. Sun, T. Lin, and Y. Q. Yu, 2016, Reservoir characteristics and controlling factors of Middle Triassic T3aL1a in Longgang area: Lithologic Reservoirs, v. 28, no. 6, p. 36–44.
Meng, Y. Z., G. S. Xu, Y. Liu, C. Yang, H. F. Yuan, and J. J. Liang, 2015, Hydrocarbon accumulation conditions of the weather crust paleokarst gas reservoir of Leikoupo Formation, West Sichuan, China: Journal of Chengdu University of Technology (Science and Technology Edition), v. 42, no. 1, p. 70–79.