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Research article

Tectonic evolution of Caledonian Palaeohigh in the Sichuan Basin and its relationship with hydrocarbon accumulation

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Abstract

The Caledonian Palaeohigh is an important gas exploration domain of Sinian and Lower Paleozoic in western Central Sichuan Basin where gas discoveries have been made successively in recent years. In order to sort out the relationship between the tectonic evolution of this Palaeohigh and hydrocarbon accumulation there, we carried out a new round of research based on previous study results. The evolution history of this Palaeohigh can be divided into seven episodes: the Late Sinian overall tilting and the youth form development of this Palaeohigh, the Cambrian-Ordovician syndepositional uplifting, the Silurian joint uplifting, the Devonian-Carboniferous uplifting and erosion, the Permian overall subsidence and deposition of regional caprock, the Triassic-Jurassic migration of structural high of the eastern segment of this Palaeohigh, and Cretaceous-Neogene strong deformation of the western segment of this Palaeohigh. The hydrocarbon accumulation in the Sinian-Lower Paleozoic experienced three evolution stages, namely the formation of ancient oil reservoirs in the Silurian-Triassic period, the development of the paleo-gas reservoirs in the Jurassic-Oligocene period, and differential evolution of gas reservoirs since the Miocene era. The Sinian-Lower Paleozoic paleo-reservoirs mainly occur in the Leshan-Ziyang-Gaoshiti-Longnǚsi zone and in the area to its north. The tectonic movement of the western segment of the Palaeohigh was strong, while its eastern segment was relatively stable since the later Himalayan epoch, which is favorable for gas accumulation and preservation. It is believed that the Gaoshiti-Moxi-Longnǚsi structural belt and its northern flank are not only favorable for the development of structural gas reservoirs in the Lower Paleozoic but also for gas reservoirs of karstic-lithologic type on the top of the Cambrian and Ordovician. The later type will be the major exploration target of this area in the future.

Keywords: Western-Central Sichuan Basin; Caledonian Palaeohigh; Tectonic evolution; Sinian; Cambrian; Early Paleozoic; Hydrocarbon accumulation; Gas reservoir formation; Exploration area

1. Introduction

Located in the western central part of the Sichuan Basin, the Caledonian Palaeohigh is also called Leshan-Longnǚsi Palaeohigh [1]. It is a basement-controlled giant skirt fringe uplift (Fig. 1). Based on the research on the parallel unconformity upper and lower isochronous surfaces at top Sinian, it is believed that this Palaeohigh had an embryonic form already in the early stage of Caledonian tectonic cycle (Tongwan stage) [2], then fell into a pattern at the end of Caledonian, experiencing multiphasic synsedimentary uplifting and denudation, so it was somewhat inherited [3]. Since the discovery of Weiyuan Sinian gas reservoir in 1964 in the Caledonian Palaeohigh, a great deal of oil and gas exploration geologic survey had been conducted, and wells Nǚji, Zishen 1, Woshen 1, Laolong 1, Zhougong 1, Gongshen 1 and Anping 1 were drilled; however, except for commercial gas flow from Well Nǚji and low yield gas flow from Well Anping 1, all the other exploration wells at the fringe of the Palaeohigh produced water [4]. Natural gas exploration was carried out in the early and middle 1990s in Ziyang area,

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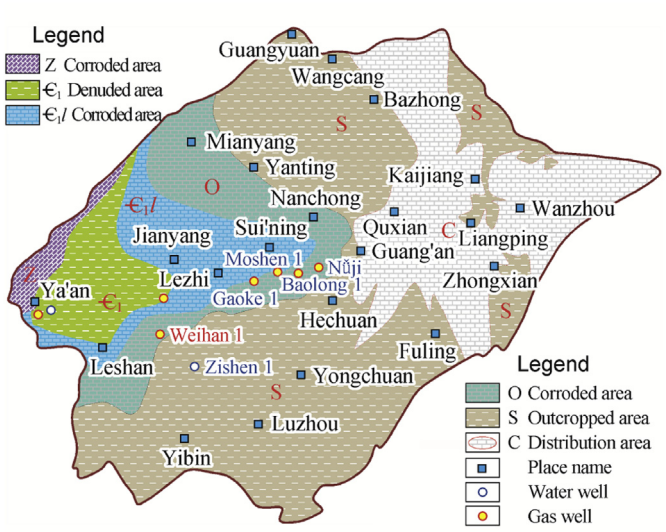

Fig. 1. Pre-Permian geologic map of the Sichuan Basin.

resulting in the discovery of Zizhong and Tiefo etc. ancient traps, and 7 wells were drilled, among which, Wells Zi 1, Zi 3 and Zi 7 obtained commercial gas flow, and their gas reserves were estimated to be 338×10^8 m^3; in the late 1990s, Well Pan 1 and Gaoke 1 were drilled, in which, Well Pan 1 encountered good quality Cambrian Longwangmiao Fm and Sinian Dengying Fm dolomite reservoirs, and Well Gaoke 1 obtained low yield gas flow from Sinian in drill stem test (DST) [4,5]. Since risk exploration started in 2004, it had been proposed for many times to re-explore the Leshan Longnǚsi Palaeohigh, and Well Moxi 1 was spud in 2006; this well finished drilling ahead of schedule in 2007 due to good shows detected in Permian; in 2008, deepening drilling was implemented in Well Baolong 1, low yield gas flow was obtained in Cambrian Xixiangchi group, and massive tight dolomite reservoirs were discovered in the Longwangmiao Fm [4]. Practice confirmed that this Palaeohigh had potential for natural gas exploration; however, there is no clear understanding of the gas accumulation and distribution pattern at this Palaeohigh, especially, the effect of tectonic evolution on gas accumulation has not been investigated thoroughly and systematically. For this reason, based on previous study results, we conducted research on the tectonic evolution of eastern central area (Weiyuan-Longnǚsi) of the Leshan-Longnǚsi Palaeohigh during 2009–2010, and made important progress in geologic understanding.

2. Tectonic evolution of the Palaeohigh

Caledonian tectonic cycle involves Late Sinian–Silurian in southern China (680–320 Ma ago) [1,2,6]. In this period, the Sichuan Basin and its adjacent areas experienced Late Sinian Tongwan movement, Early Cambrian Xingkai movement, Yunan movement at last stage of Cambrian, Duyun movement at last stage of Ordovician, Silurian Guangxi movement and so on [1,6]. The Caledonian Palaeohigh in Central Sichuan Basin was formed against the background of the above continuous strong tectonic movements.

2.1. Tectonic evolution features at the early stage of Caledonian cycle

The early stage of Caledonian tectonic cycle refers to the development stage of Late Proterozoic Sinian. The tectonic movement occurred at this stage in the Upper Yangtze region is called Tongwan movement, which includes two episodes of stronger tectonic movements: episode I of Tongwan and episode II of Tongwan. Episode I of Tongwan refers to the tectonic movement happened after the deposition of the 2nd member of the Dengying Fm, whereas episode II of Tongwan refers to the tectonic movement after the deposition of the 4th member of the Dengying Fm. The Caledonian Palaeohigh region in Central Sichuan Basin in the Tongwan stage couldn't actually be called Palaeohigh, for it was just an irregular karstic ancient landform developed on a large slope high in the southeast and low in the northwest [5,7]. This can be seen from a number of seismic profiles: Sinian, thick in the southeast and thin in the northwest, indicates that the tectonic evolution was dominantly tilting. 2006WW31.5 seismic profile shows that after episode II of Tongwan tectonic movement, the upper part of Sinian was thick in the southeast and thin in the northwest (Fig. 2). The research by Huang Jizhong et al. proved that the relative relief of the upper and lower land forms on the unconformity of top Sinian exceeded 300 m in the Weiyuan-Longnǚsi area [2]. The development of this regional unconformity means that the late stage of Tongwan was favorable for the formation of large area of Sinian karstic reservoirs.

2.2. Tectonic evolution features at the middle-late stage of Caledonian cycle

The middle-late stage of Caledonian cycle refers to the tectonic movement happened in the Cambrian-Silurian depositional stage [2,7,8]. This stage, the major development stage of Central Sichuan Palaeohigh, witnessed frequent tectonic movement in the Upper Yangtze region [9]. It can be seen from Fig. 3 that the Caledonian Palaeohigh of Central Sichuan Basin had distinct features at the early stage of Early Cambrian. It was mainly developed in Gaoshiti-Longnǚsi-Guang'an zone, and Weiyuan-Ziyang area was the saddle between the Leshan Palaeohigh and the Longnǚsi Palaeohigh. At

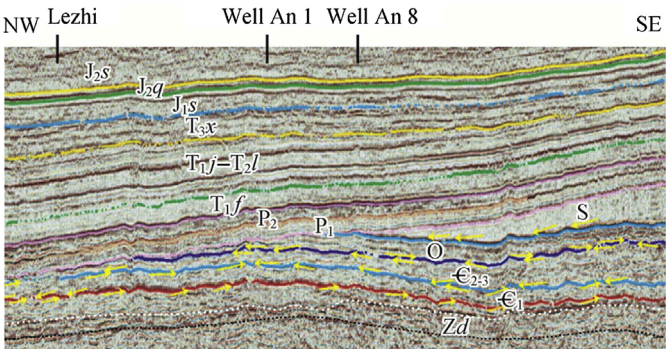

Fig. 2. 2006WW31.5 Seismic profile of the Sichuan Basin.

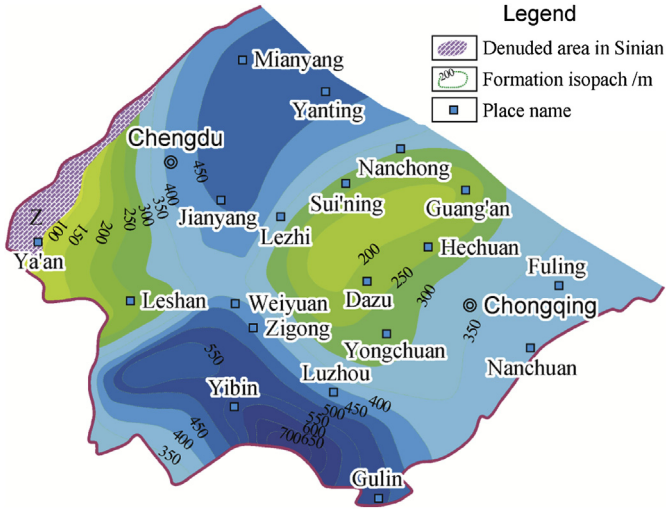

Fig. 3. Residual thickness of Lower Cambrian Qiongzhusi Fm in south Central Sichuan Basin.

this stage, the development of the Caledonian Palaeohigh in Central Sichuan Basin featured coexistence of subsidence and uplifting.

2.2.1. Cambrian-ordovician syndepositional uplifting stage

The tectonic movement happened at the early stage of Cambrian is called Xingkai movement [2,7,8], which is obvious in western and northwestern Sichuan Basin [3]. At this stage, the Cambrian strata in Central Sichuan Basin had both onlap and denudation. Fig. 2 shows that there was northwestward onlap at the early stage of Cambrian, meanwhile, there was truncation at the top of Lower Cambrian; Fig. 3 shows that the Qiongzhusi Fm was thinner in the Palaeohigh region and thicker in the depression area, confirming that the Palaeohigh strongly controlled the deposition. The tectonic movement took place at the late stage of Cambrian is named Yu'nan movement, which is obvious in the Palaeohigh region and the Guizhou area [2,7,8]. Northwestward onlap and apparent Middle-Upper Cambrian top truncation existed in the Palaeohigh region. Therefore, at the stages of Xingkai movement and Yu'nan movement, both subsidence deposition and apparent uplifting denudation occurred in Central Sichuan Basin, and the Caledonian Palaeohigh had certain control over the deposition.

In the Upper Yangtze region, the tectonic movement occurred at the late stage of Ordovician is called Duyun movement, which is a tectonic movement at the middle stage of Caledonian tectonic cycle [2,7,9]. The tectonic evolution of the Caledonian Palaeohigh region at that time was similar to that in Middle and Late Cambrian, including overlap deposition at early Ordovician and uplifting denudation at late Ordovician. Fig. 2 shows that there was apparent northwestward onlap in the Anpingdian area at the initial stage of Ordovician; after the deposition of Ordovician, affected by the violent uplifting tectonic movement at the middle stage of Caledonian, an apparent truncation unconformity was developed in the Anpingdian area and the area northwest of it.

Therefore, three times of overlap deposition and three times of uplifting denudation occurred in Cambrian–Ordovician, among which, the uplifting denudation at the end of Cambrian and Ordovician was most severe.

2.2.2. Joint uplifting stage in Silurian

In the Upper Yangtze region, the tectonic movement happened at the last stage of Silurian is called Guangxi movement (320 Ma ago), and is a tectonic movement at the late stage of Caledonian tectonic cycle [9]. Owing to the convergence action of the Yangtze continental block and the Huaxia continental block, a foreland basin was formed in Silurian [10,11]. The basin after uplifting was located in the northwest of the arching faulted zone formed jointly by the Jiangnan faulted zone and the E-Xiang-Qian faulted zone, i.e., the major region of present Sichuan Basin [12–14]. Fig. 1 shows that Silurian was mainly developed in the peripheral zone of the Caledonian Palaeohigh in Central Sichuan Basin, whereas Leshan-Longnǚsi was joined together, with erosion intensity strengthened and outcropped strata becoming older from the east to the west. Fig. 2 shows that Silurian onlapped Ordovician, and numerous Silurian onlaps existed in the southeast area of Anpingdian; meanwhile, Devonian and Carboniferous were not deposited on Silurian, confirming that at the last stage of Silurian, the Caledonian Palaeohigh region was uplifted and denuded as a whole in Central Sichuan Basin, and formed parallel unconformity contact with Permian. Fig. 4 shows that the Caledonian Palaeohigh was joined together from two separated large Palaeohighs at the early stage, and the highs of palaeotectonic zone were located in the northern area of Leshan, Jingyan, Ziyang, Lezhi, Gaoshiti and Longnǚsi. Therefore, Silurian was a period when the Leshan Palaeohigh and the Longnǚsi Palaeohigh were both uplifted and denuded.

In conclusion, at the middle-late stage of Caledonian cycle, this region experienced two development stages, Cambrian-

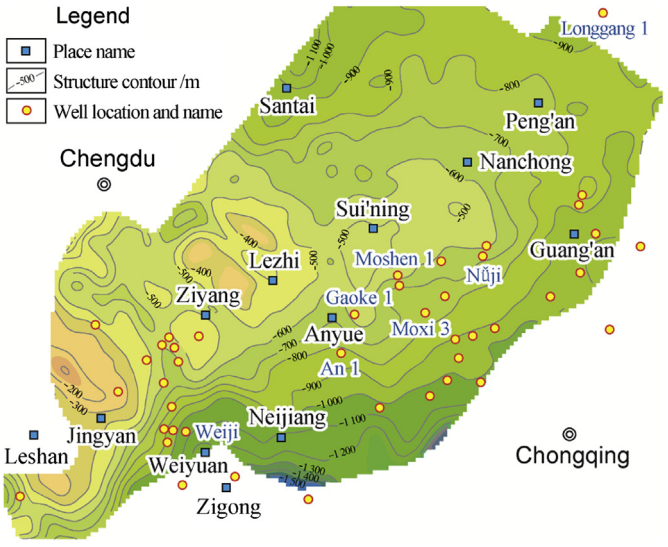

Fig. 4. Structural map of Qiongzhusi Fm bottom before Silurian deposition in the Caledonian Palaeohigh of Central Sichuan Basin.

Ordovician syndepositional uplifting and Silurian joint uplifting. The subsidence and filling in the deposition at the early stage of Xingkai movement formed the first set of high-quality thick source rocks in the Caledonian Palaeohigh region of Central Sichuan Basin; the Duyun movement at the late stage of Caledonian gave rise to the foreland basin, causing the Silurian to develop overlap deposition surrounding the joint Palaeohigh, and thus formed Lower Silurian Longmaxi Fm high-quality source rocks. Five regional unconformities were formed in the Caledonian Palaeohigh region of Central Sichuan Basin by Xingkai movement, Yu'nan movement, Duyun movement and Guangxi movement respectively: unconformity at the lower part of Lower Cambrian, unconformity between Lower Cambrian and Middle Cambrian, unconformity between Middle-Upper Cambrian and Ordovician, unconformity between Ordovician and Silurian, and unconformity between Silurian and Neopaleozoic, which provide favorable conditions for the development of multiple series of strata karstic reservoirs in the region.

2.3. Tectonic evolution features in Hercynian

Two relatively strong tectonic activities, Yunnan movement and Dongwu movement happened in the Upper Yangtze region at the Hercynian tectonic cycle stage. The evolution of the Caledonian Palaeohigh in Central Sichuan Basin experienced two evolutionary processes, the long-term uplifting denudation and overall subsidence deposition.

2.3.1. Devonian-Carboniferous uplifting denudation stage

At the early stage of Hercynian, not only the overall uplifting pattern at the last stage of Caledonian continued in the Sichuan Basin, but also Yunnan movement occurred (270 Ma ago) [15]. At that time, most areas of the basin had rose out of the sea, and suffered weathering and denudation for a long time since Devonian-Early Carboniferous, and only restricted Devonian developed in the basin margin areas like the northeastern and western Sichuan Basin [16] and thin Upper Carboniferous carbonate deposited in the northeastern Sichuan Basin (Fig. 1); furthermore, affected by the Yunnan movement at the last stage of Carboniferous, the Sichuan Basin was uplifted as a whole once more, and the Caledonian Palaeohigh region in Central Sichuan Basin was further denuded [17]. The seismic profile in Fig. 2 also shows that the depositional thickness of Lower Permian is relatively uniform, indicating that the Caledonian Palaeohigh developmental area in Central Sichuan Basin was in an uplifting denudation state as a whole from Devonian to Carboniferous. Therefore, the Caledonian Palaeohigh region in Central Sichuan Basin was also characterized by uplifting denudation at that stage.

2.3.2. Permian regional subsidence and deposition stage

At the late stage of Hercynian, the Caledonian Palaeohigh in Central Sichuan Basin was characterized by overall subsidence, transgression and acceptance of deposits, and it was obviously affected by the Dongwu movement [6,18,19]. At the initial stage of Dongwu movement, affected by the Emei taphrogeny, the taphrogenic activity in the basinal periphery extended towards the inside of the Basin, regional subsidence and transgression occurred in the Upper Yangtze region, and a set of Liangshan Fm thin bauxitic mudstones and shale deposits was developed regionally. Developed sparsely in the Palaeohigh region of Central Sichuan Basin, the Liangshan Fm is 0–20 m thick, showing the feature of fill-leveling at the early stage of deposition [20]. Afterwards, a set of Qixia Fm-Maokou Fm thick carbonate deposits was developed regionally [6,21]. The seismic profile in Fig. 2 shows that the formation thickness of Permian is basically the same, indicating that the deposition was dominantly overall subsidence and acceptance of marine carbonate deposits at that time. At the late stage of Dongwu movement, the Emei taphrogeny was strengthened, not only volcanic rock intruded on a large scale in the periphery of the Basin, but also the basin was uplifted as a whole, 8-9 Ma depositional hiatus occurred, and the embryonic forms of Palaeohighs like Luzhou-Kaijiang were formed [19,21]. The Caledonian Palaeohigh region in Central Sichuan Basin was located on the west slope of Luzhou-Kaijiang Palaeohigh, where the Maokou Fm at top Lower Permian was denuded to a certain degree. At the last stage of Dongwu movement, subsidence and transgression occurred in this region, a set of paralic Longtan Fm coal measure strata was formed, later on, platform facies reef and shoal carbonate deposits were developed [22]. It can thus be seen that the Caledonian Palaeohigh in Central Sichuan basin subsided as a whole in Permian, receiving the first set of sedimentary cap in the Caledonian Palaeohigh.

In a word, the Caledonian Palaeohigh underwent two obviously different evolution stages in the Hercynian tectonic movement. At the early and middle stages of Hercynian, overall uplifting predominated this region, resulting in the denudation of the Cambrian-Silurian strata to various degrees, and the formation of extensive karst reservoirs in the Cambrian and Ordovician carbonate formations. At the late stage of Hercynian, overall subsidence deposition predominated this region, giving rise to the first set of regional carbonate deposits on the Lower Palaeozoic weathered crust in the Caledonian Palaeohigh, which, together with the coal measure mud shale formed at the early stage of Late Permian, constitutes the regional caprock on the large unconformity of the Caledonian Palaeohigh.

2.4. Tectonic evolution features in Indosinian-Middle Yanshannian

The Caledonian Palaeohigh in Central Sichuan Basin was in a differential evolution stage in Indosinian-Middle Yanshannian [23]. At this stage, the tectonic evolution of the Leshan-Ziyang Palaeohigh was apparently different from that of the Longnǚsi Palaeohigh.

Figs. 5 and 6 show that in Indosinian, although the structural highs in the Leshan-Ziyang area at the western section of the Caledonian Palaeohigh moved southward to a certain degree, they were relatively stable; prior to the deposition of Triassic, the Cambrian structural highs in the Palaeohigh

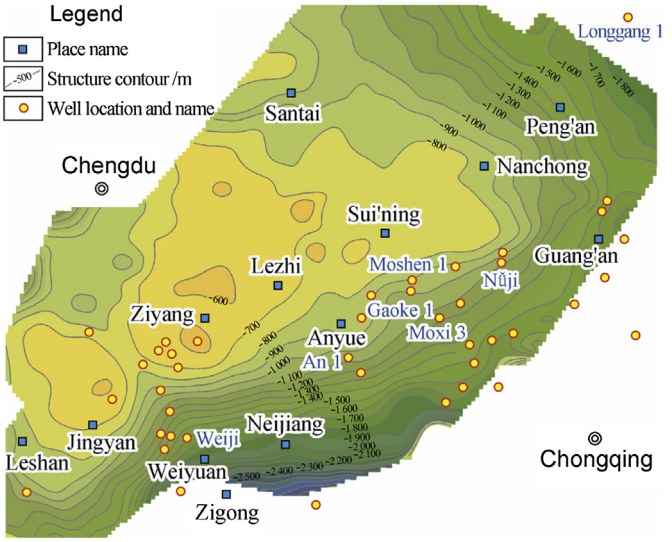

Fig. 5. Structural map of Longwangmiao Fm top prior to the deposition of Triassic in Central Sichuan Basin.

region steadily developed in the Leshan-Ziyang area and the area north of it. At this stage, Leshan and Ziyang in the west of the Caledonian Palaeohigh were the structural highs of the two Palaeohighs respectively, and Weiyuan was still in the saddle slope area on the southern side of the two Palaeohighs. Whereas prior to the deposition of Triassic, the axial line of Cambrian structural highs in the Gaoshiti-Longnǚsi area at the eastern section of the Palaeohigh region moved southward from the northern Lezhi-Sui'ning line to the Gaoshiti-Anpingdian-Moxi-Longnǚsi line, and apparent subsidence characteristics occurred in the Moxi-Longnǚsi area. The southward move of the structural high axial line in Central Sichuan Basin and the formation of Indosinian Luzhou Palaeohigh [23] were related to the Indosinian movement in the eastern region of the Caledonian Palaeohigh, and the

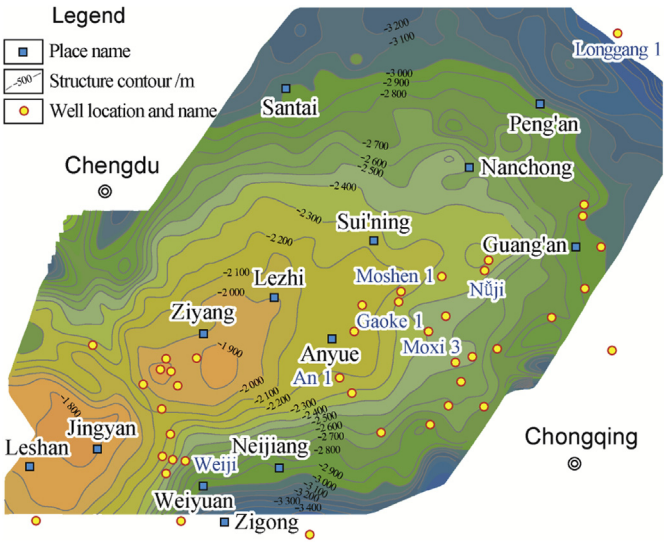

Fig. 6. Structural map of Longwangmiao Fm top prior to the deposition of Upper Triassic in Central Sichuan Basin.

tectonic movement at the early stage of Indosinian made the southeastern part of this region uplift and northwestern part subside. Fig. 2 also shows that the Middle-Lower Triassic suffered from strong denudation in the Anpingdian and its southeast, and the denudation of the Middle-Lower Triassic became greater southeastward.

In Jurassic-Early Cretaceous, intracontinental compression occurred in the Qinling Mountains, giving birth to the northern Sichuan depression on its southern foot, and a batch of near EW – NE trend and northeast plunge gentle nose-like uplifts in the southwestern part of the basin [7,23,24]. The Palaeohigh region of Central Sichuan basin, located in the downdip of these nose-like uplifts, experienced steady subsidence and deposition; as is shown in Fig. 2, at that time, Jurassic, very small in thickness difference, mainly saw isostatic subsidence.

It can thus be seen that in Indosinian-Middle Yanshannian, the west section of the Caledonian Palaeohigh in Central Sichuan Basin was relatively stable, whereas in the east, affected by Indosinian Luzhou Palaeohigh uplifting, the structural highs moved southward apparently.

2.5. Tectonic evolution features in late Yanshannian-Himalayan

The tectonic evolution of the Caledonian Palaeohigh in late Yanshannian-Himalayan was apparently different from that in Indosinian-Middle Yanshannian, i.e., the Gaoshiti-Longnǚsi in the eastern section of the Palaeohigh was relatively stable, whereas the Leshan-Ziyang in the western section of the Palaeohigh suffered strong folding, and its structural highs moved southward apparently [24,25]. In Late Cretaceous, since the Yangtze block was strongly compressed by the crustal stress coming from the southeast direction, the southeast of the Mesozoic continental basin in the Upper Yangtze region was affected, and the sedimentary cap severely deformed, giving birth to some anticlines west of the Qiyaoshan Mountain in the basin [1,23]. From the early stage of Himalayan to the end of Oligocene, compressed by the Pan-Pacific structural domain, the widespread barrier folds were formed in the eastern Sichuan region, whereas the Weiyuan structure was further uplifted and fell into a pattern [23,26], and the folds of Moxi-Longnǚsi structure were strengthened to some extent.

Figs. 6 and 7 show that in Himalayan, the Gaoshiti-Anpingdian-Longnǚsi Palaeohigh region was relatively stable, only the subsidence was larger in the east section, and Guang'an fold anticline was formed due to the compression of the Huayingshan thrust belt. however, in the Ziyang-Weiyuan area, the structural highs moved apparently, i.e., the original structural high of Ziyang Palaeohigh was transformed into a slope area, and the low-lying area of the Weiyuan slope was transformed into a large anticlinal structure, folded and uplifted from 7500–8000 m buried depth to 2800–4000 m depth [27,28], showing the tectonic evolution features of moving southward of structural highs at the western section of the Caledonian Palaeohigh in Central Sichuan Basin.

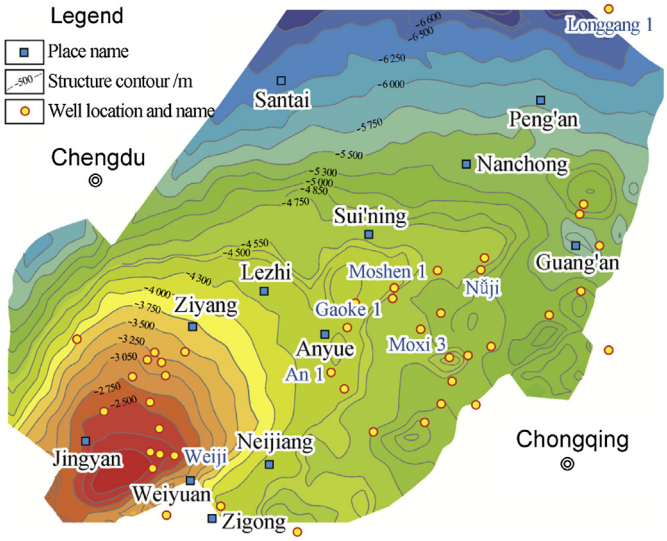

Fig. 7. Structural map of Longwangmiao Fm top in the Caledonian Palaeohigh region of Central Sichuan Basin.

In conclusion, the Caledonian Palaeohigh in Central Sichuan Basin experienced seven evolution stages: overall tilting and embryonic form formation in Sinian, syndepositional uplifting in Cambrian-Ordovician, joint uplifting in Silurian, long-term uplifting denudation in Devonian-Carboniferous, overall subsidence deposition in Permian, variation at eastern section in Triassic-Jurassic, and southward movement of structural highs of the western section in Cretaceous-Neogene.

3. Tectonic evolution of Palaeohigh and hydrocarbon accumulation

The key to hydrocarbon accumulation and reservoir formation is the effective configuration of such elements as hydrocarbon sources, reservoirs and traps. From the hydrocarbon source conditions of the Caledonian Palaeohigh and previous studies show that three sets of effective source rocks mainly developed, i.e., the lower segment of the 3rd member of the Sinian Dengying Fm, the Lower Cambrian Qiongzhusi Fm and the Lower Silurian Longmaxi Fm [4]. The reservoirs are dominantly dolomite and karst reservoirs formed in Sinian Deng II member and Deng IV member at Tongwan stage, as well as in the Longwangmiao Fm, the Xixiangchi group and Ordovician at Caledonian stage [5,29]. The traps mainly consist of structural traps, karst type stratigraphic or lithologic traps formed in different geologic periods [5,30]. The Sinian-ordovician hydrocarbon accumulation in the Caledonian Palaeohigh mainly experienced three evolution stages, namely the development of large area of palaeo-oil reservoirs, the development of palaeo-gas reservoirs and the differential evolution of gas reservoirs.

3.1. End of Caledonian – Indosinian – formation stage of palaeo-oil reservoirs

The Sinian Deng III lower member source rocks and the Qiongzhusi Fm source rocks in southern Sichuan sag entered oil-generation peak at the last stage of Caledonian tectonic movement; but in the Palaeohigh region of Central Sichuan Basin, they reached oil-generation peak in late Hercynian-Indosinian [30,31]. Combined with the palaeostructure development characteristics at that time, substantial oil and gas generated prior to Indosinian all were accumulated in the palaeo-anticlinal trap development areas like Jingyan-Ziyang-Lezhi-Sui'ning-northern Longnǚsi area (Figs. 4, 7 and 8). From the end of Caledonian to Hercynian, the oil and gas accumulated in the Palaeohigh mainly came from the southern Sichuan sag region, and they were mainly accumulated in the Sinian and Cambrian reservoirs. At that time, for the sedimentary cap was not developed or developed poorly in the

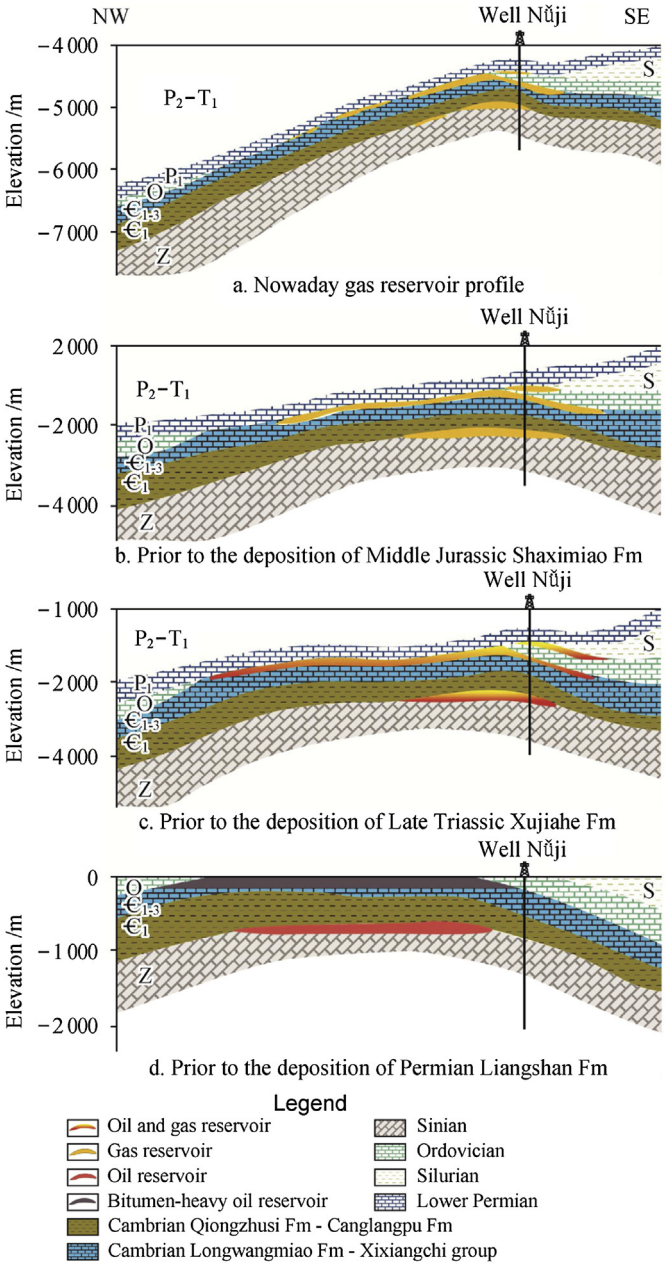

Fig. 8. Evolution profile of Sinian-Lower Palaeozoic oil and gas reservoirs in the Longnǚsi area of the Sichuan Basin.

Caledonian Palaeohigh, the palaeo-oil reservoirs were mostly destroyed to various degrees, resulting in the development of heavy oil reservoirs and bitumen reservoirs [3,4,32]. But in Indosinian, the oil and gas accumulated in the Palaeohigh mainly came from the source rocks in the Palaeohigh region, which entered the hydrocarbon-generation peak period at that time. Meanwhile, the weathered crust became the important hydrocarbon-migrating channel; oil and gas are likely to accumulate in Sinian, Cambrian and Ordovician, and palaeo-oil reservoirs were mainly developed in the Leshan-Ziyang-Gaoshiti-Longnǚsi zone and in the area north of it (Figs. 6 and 8).

3.2. Yanshanian – early Himalayan: formation stage of palaeo-gas reservoirs

In Yanshanian-early Himalayan, the Caledonian Palaeohigh region in Central Sichuan Basin mainly underwent subsidence deposition, and only weaker folding deformation occurred in the Weiyuan area. At that time, the three sets of source rocks entered the massive gas generation stage; meanwhile, since the palaeo-oil reservoirs in the Caledonian Palaeohigh were buried relatively deep at around 6000–7000 m, the liquid hydrocarbon in the palaeo-oil reservoirs was cracked into gaseous hydrocarbon in a great deal, and the Indosinian palaeo-reservoirs were transformed into natural gas reservoirs (Fig. 8). A great deal of dry bitumen was found in the.

Sinian-Cambrian reservoirs of the Caledonian Palaeohigh, confirming that the gas reservoirs in the Caledonian Palaeohigh were mostly crude cracked gas, and gas cap gas of restricted palaeo-oil reservoirs was developed only in the Ziyang area [6,33]. Therefore, in Yanshanian-early Himalayan, the Lower Palaeozoic-Sinian in the Caledonian Palaeohigh of Central Sichuan Basin were mainly characterized by the formation of palaeo-gas reservoirs, which were mainly developed in the Leshan-Ziyang-Gaoshiti-Longnǚsi zone and the area north of it.

3.3. Late Himalayan: differential evolution stage of gas reservoirs

It is known from the above tectonic evolution analysis that at that stage, the tectonic evolution in the eastern section of the Caledonian Palaeohigh was largely different from that in the western section. Since the last stage of Oligocene, the tectonic movement had been intense in the western section of the Palaeohigh, characterized by strong folding and uplifting; whereas the eastern section had been relatively stable, characterized by overall uplifting and local fold strengthening. For instance, the Weiyuan area not only was transformed from slopes into large anticlines, but also was greatly uplifted by 4000–4700 m; the Ziyang Palaeohigh was transformed into a down dip slope area at the north flank of the Weiyuan mega-anticline. Some natural gas in the Ziyang palaeo-gas reservoir was migrated southward into the Weiyuan structure, and only a small amount of gas cap gas accumulated in the palaeo-oil reservoir remained [34]; as for the Weiyuan structure, affected by strong folding and uplifting, it received not only some natural gas migrated from the Ziyang palaeo-gas reservoir, but also the natural gas resulted from depressurization and exsolution of substantial water soluble gas [35].

In the Gaoshiti-Moxi-Longnǚsi area, for the structure was relatively stable at that stage, only Moxi, Longnǚsi and Guang'an structures were strengthened to some extent, the accumulation of gas in Sinian-Ordovician was concentrated in the area where structural traps were developed in an inherited pattern. Just because the Gaoshiti, Anpingdian, Moxi, Longnǚsi and Guang'an structures at eastern section of the Caledonian Palaeohigh were relatively stable at that stage, and the structural faults in the Sinian, Cambrian and Ordovician reservoirs were not developed or developed poorly, the dissipation of gas was inhibited. Therefore, the Lower Palaeozoic-Sinian in the eastern section of the Caledonian Palaeohigh in Central Sichuan Basin had favorable preservative conditions.

However, in the western section of the Palaeohigh, because the tectonic movement was violent, the structural traps of Weiyuan and southwest of it were formed later, and the natural gas generated at hydrocarbon-generation peak time was not captured; furthermore, the fracture development and preservation conditions were poor, even if the Weiyuan anticline was supplied by dual gas source gas, the fullness of gas in it was still very low [26]. Therefore, the large-scale accumulation conditions of natural gas in the western section of the Caledonian Palaeohigh in Central Sichuan Basin were poorer than in the eastern section.

It can thus be seen that the accumulation of oil and gas in the Caledonian Palaeohigh of Central Sichuan basin experienced three stages, formation of palaeo-oil reservoirs from the end of Caledonian to Indosinian, formation of palaeo-gas reservoirs in Yanshanian-early Himalayan, and differential evolution of gas reservoirs in late Himalayan. Especially, the last one brought about large difference in the preservation conditions of natural gas in the Palaeohigh, resulting in a pattern of gas accumulation conditions good in the west and poor in the east.

4. Conclusions

1) The Caledonian Palaeohigh in Central Sichuan Basin experienced seven major tectonic evolution stages: overall tilting and embryonic form development at the early stage of Caledonian cycle, syndepositional uplifting at the middle stage of Caledonian cycle, joint uplifting at the late stage of Caledonian cycle, long-term uplifting denudation at the early and middle stages of Hercynian cycle, overall subsidence deposition and formation of regional seal of the Palaeohigh at the late stage of Hercynian cycle, stable at the western section and southward moving of structural highs at the eastern section of the Palaeohigh in Indosinian-Middle Yanshannian, and stable at the eastern section and violent deformation at the western section of the Palaeohigh in late Yanshannian-Himalayan.
2) The hydrocarbon accumulation in Caledonian Palaeohigh of Central Sichuan Basin experienced three main periods:

formation of palaeo-oil reservoirs in Silurian-Triassic, development of palaeo-gas reservoirs in Jurassic-Oligocene, and differential evolution of gas reservoirs since Miocene; and the palaeo-oil reservoirs and palaeo-gas reservoirs were mainly developed in the Leshan-Ziyang- Gaoshiti-Longnǚsi zone and the area north of it.

3) Since late Himalayan, the Gaoshiti-Longnǚsi area at the eastern section of the Caledonian Palaeohigh in Central Sichuan Basin had been relatively stable, with weak tectonic movement and a few developed faults and fractures, which were favorable for large-scale accumulation and preservation of Lower Palaeozoic natural gas; while in the Leshan-Weiyuan-Ziyang area at the western section of the Palaeohigh, strong folding and deformation occurred, so only remnant or some migrated gas and water soluble gas resulted from uplifting and exsolution were accumulated and preserved.
4) The Gaoshiti-Moxi-Longnǚsi structural zone and its north flank not only are the favorable development areas of Sinian-Lower Palaeozoic palaeo-oil reservoirs and palaeo-gas reservoirs, but also are the most favorable regions for present gas accumulation and reservoir formation. The karst lithologic traps are widely developed in Sinian and at the top Lower Palaeozoic of this region, so they are also the favorable domains for exploration of new type of natural gas.

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