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Research article

Stratigraphic sequence and sedimentary characteristics of Lower Silurian Longmaxi Formation in Sichuan Basin and its peripheral areas

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Abstract

A high-precision sedimentary environment study of the Lower Silurian Longmaxi Formation is an important subject for shale gas exploration and development in Sichuan Basin and its surrounding areas. On the basis of outcrops and drilling data, its isochronous stratigraphic framework was built according to a particular graptolite zone and an important marker bed, and lithofacies, paleontology, calcareous content, well logging, geochemistry and other geologic information were combined to describe the sedimentary microfacies of Longmaxi Formation and its stratigraphic sequence, sedimentary evolution process and high quality shale distribution features as follows: ① with regional diachronism of the top and the bottom, the Longmaxi Formation is divided into two third-order sequences (SQ1 and SQ2), of which SQ1 is mainly an abyssal sedimentary assemblage deposited in the marine transgression period, and SQ2 is a bathyal to shallow sea sedimentary assemblage deposited in the marine regression period; ② there are eight microfacies such as deep calcareous shelf and deep argillaceous shelf in this formation and the organic-rich shale was mainly deposited in the deep water area of SQ1; and ③ from SQ1 to SQ2, the depocenter moved from the depression area in southern-eastern to northern Sichuan Basin, but the central Sichuan uplift remained an underwater one. It is concluded from this study that: ① shale gas production layers were mainly deposited in SQ1, the southern-eastern depression area was the depocenter in SQ1 and a shale gas enrichment area; and ② black shale in northern Sichuan was deposited in late SQ2, with limited distribution and relatively insufficient exploration potential, but the potential of shale gas exploration in western Hubei area is between southern-eastern and northern Sichuan Basin.
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Keywords: Sichuan Basin; Peripheral areas; Lower Silurian; Demirastrites; Spirograptus; Stratigraphic sequence; Sedimentary microfacies; Black shale; Shale gas; Exploration potential

The Lower Silurian Longmaxi Formation in Sichuan Basin and its peripheral areas has become the realistic domain of China's shale gas development [1–7]. As assessment work continues and deepens, studies on major factors that control the shale gas enrichment and high productivity in this formation are becoming increasingly popular in the industry [1,4,8–13]. Sedimentary environment, as a critical geological factor for the formation of high-quality shale reservoirs, is undoubtedly one of the major controlling factors.

Generally, the Longmaxi Formation is a graptolite shale stratum with less obvious sedimentary cycles and simple log response features [9]. A critical subject in exploration and development is how to conduct fine sedimentary environment study. Liang Digang et al. [2,14–16] concluded three major difficulties in high-precision sedimentary environment study of the Longmaxi Formation: ① how to produce a reasonable division of third-order sequence and build a regional isochronous stratigraphic framework; ② how to build an effective marker for dividing microfacies by using drilling, core and log data; and ③ how to judge the property of the Central Sichuan paleo-uplift, i.e., is it an underwater uplift or a provenance?

Firstly, on the basis of drilling and outcrop data from the study area, an appraisal well which penetrated a complete

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interval from the Upper Ordovician Wufeng Formation to the Lower Silurian Longmaxi Formation, covering a variety of sedimentary microfacies and having abundant geologic data (e.g., core, log and testing data), was selected to create a standard section; the biostratigraphic framework of that profile is built based on paleobiocenose, and the sequence framework was established according to a particular graptolite zone and other marker beds. Secondly, core description, log response and experimental measurement data were applied to calibrate the sequence, lithofacies and sedimentary facies of the standard section, and a multi-information marker for recognizing sequence boundary and sedimentary microfacies was produced to conduct sequence and sedimentary facies division at outcrops and other drilling locations in the study area. Finally, by mapping sedimentary facies for each sequence, the lithofacies paleographical and evolution characteristics of the Longmaxi Formation in the study area were analyzed, and the control of sedimentary environment on black shale was pointed out. This study expects to provide a basis for shale gas zone selection and enrichment law research.

1. Stratigraphic sequence of the Longmaxi Formation

The Longmaxi Formation is a Silurian Lower Llandovery graptolite shale stratum that is widely distributed across the middle and upper Yangtze regions [17,18]. Different graptolite zones are regionally isochronous and roughly representative of a particular range of water depth [2,17]. Thus, the widespread graptolite zone that is easy to recognize provides an important marker for dividing the sequence boundary and sedimentary environment of the Longmaxi Formation.

1.1. Biostratigraphy

Regionally, the thickness of the Longmaxi Formation varies considerably, ranging in 300−600 m in the southern Sichuan and eastern Sichuan−western Hubei, 50−300 m in the northern Guizhou, and 20−300 min the northern Sichuan−southern Shanxi [2,5,9]. Now, the Longmaxi Formation biostratigraphy has been recognized basically. It is considered that, the Lower Llandovery can be generally divided into three stages and eleven graptolite zones: from lower to upper, the Rhuddanian (*Normalograptus persculptus*, *Akidograptus ascensus*, *Parakidograptus acuminatus*, *Cystograptus vesiculosus*, *Coronograptus cyphus*), the Aeronian (*Demirastrites triangularis*, *Demirastrites pectinatus-Monograptus argenteus Lituigraptus convolutus*, *Stimulograptus sedgwickii*), and the Telychian (*Spirograptus guerichi*, *Spirograptus turiculatus*) [17]. This provides an important basis for building an isochronous stratigraphic framework.

The top and bottom of the Longmaxi Formation appear to be regionally diachronous in the Upper Yangtze region. In the southern Sichuan Basin, the combined Wufeng−Longmaxi formations are a set of continuously deposited shale stratum (Fig. 1) in which some typical fossils are seen, including *Hirnantian Brachiopoda*, *Rhuddanian Akidogroptus*, *Aeronian Demirastrites* and *Telychian Spirographtus* (Fig. 2). Three stages (i.e., Rhuddanian, Aeronian and Telychian) and eleven graptolite zones were deposited in the Weiyuan−Huaying region, and two stages (i.e., Rhuddanian and Aeronian) and nine graptolite zones were developed in the Changning−Luzhou region where the Telychian is absent. In the northern Sichuan Basin, the Wufeng Formation and Rhuddanian and Aeronian are absent, and only the Telychian was deposited. In the eastern Chongqing−western Hunan and Hubei regions, the bottom of the Longmaxi Formation lies between *N. persculptus* zone and *Coronograptus cyphus* zone, penetrating a total of two stages and five graptolite zones; and its top lies between *Demirastrites pectinatus-Monograptus argenteus* zone and *Spirograptus guerichi* zone, penetrating a total of two stages and four graptolite zones [17]. According to its biostratigraphy, the top and bottom of the Longmaxi Formation are judged to be diachronuous in the Sichuan Basin and its peripheral areas, and, from southeast to northwest, the strata tend to be younger and the depocenter moves towards the northwest.

The underlying Hirnantian lumachelle (containing *Hirnantia Brachiopoda*) and Aeronian *Demirastrites triangulatus* zone are most widely distributed. They are representative of the shallowing of water bodies and easy to recognize. They also provide an important marker bed for regional correlation of the Longmaxi Formation (Fig. 1).

1.2. Sequence stratigraphy

The authors built the general stratigraphic section of shale formations in the Longmaxi Formation (Fig. 1) on the basis of drilling, core, log, paleontological, geochemical, and rock-mineral data of the Wufeng−Longmaxi formations obtained from Well W201 in the southern Sichuan Basin. Furthermore, based on graptolite assemblage, lithofacies and electric characteristics recorded in Changning and Huaying regions, the Longmaxi Formation was divided into two third-order sequences:

SQ1 and SQ2 (Figs. 1 and 3). SQ1 is bordered to the bottom by the top of Hirnantian lumachelle and to the top by the top of Aeronian Demirastrites triangulates shale section (i.e., the valley bottom of Natural-Gamma Ray curve at Lower Aeronian). SQ2 is bordered to the top by a transitional surface between the Longmaxi Formation graptolite shale and the Lower Silurian Niulanshan Formation calcareous shale (in the Changning block) and grayish green clay shale (in the Weiyuan−Huaying region) with scarce graptolite. The essential features of these two third-order sequences will be discussed immediately.

SQ1 is the sequence at the base of the Rhuddanian−Aeronian, containing a total of six graptolite zones: *Normalograptus persculptus*, *Akidograptus ascensus*, *Parakidograptus acuminatus*, *Cystograptus vesiculosus*, *Coronograptus cyphus* and *Demirastrites triangulatus*. The maximum flooding surface is located at the peak of natural gamma-ray in the Upper Rhuddanian, representing deep-water facies graptolite shale sedimentary formation of the early Longmaxi Formation. The depocenter of SQ1 is located within the

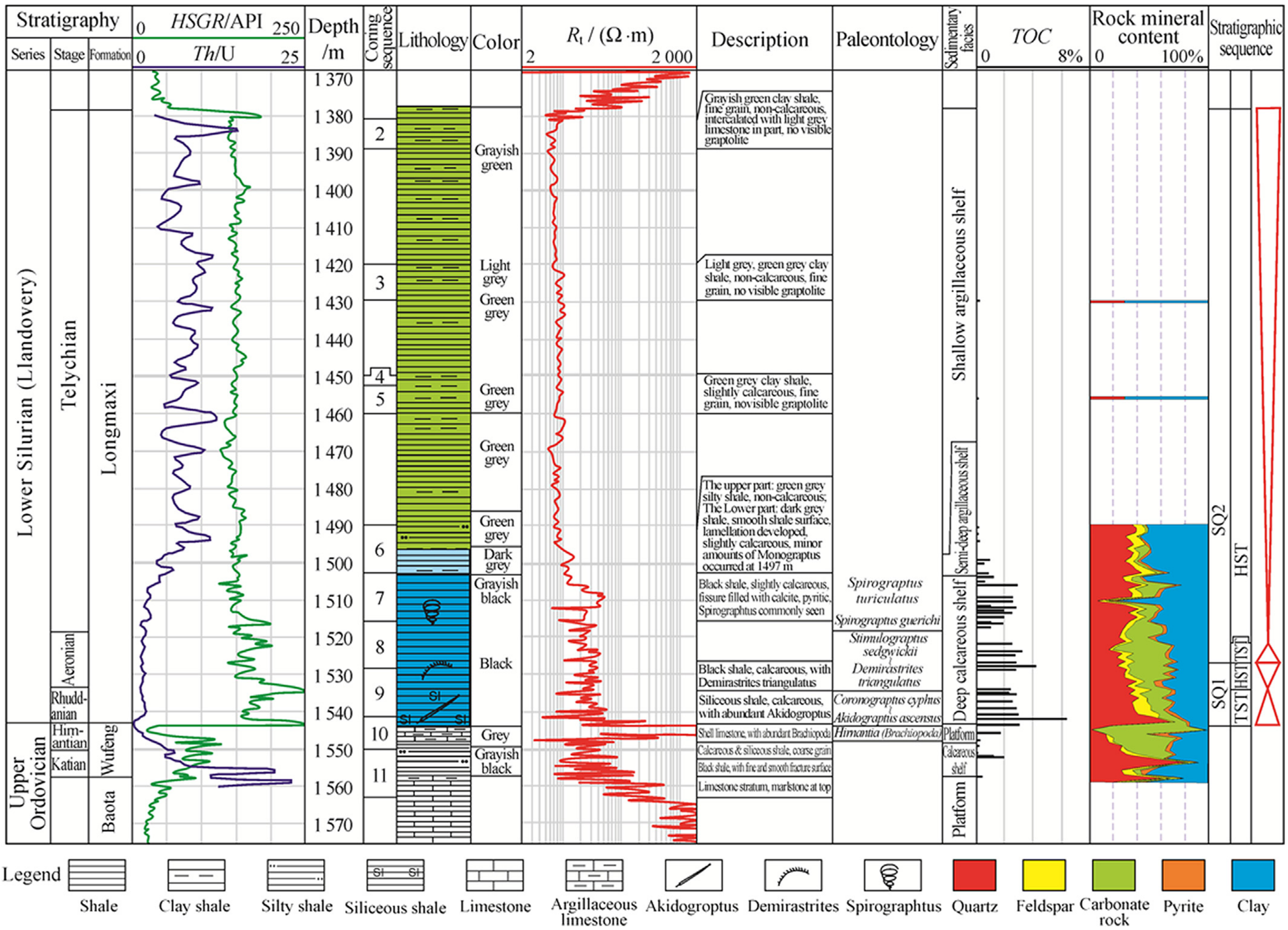

Fig. 1. Comprehensive histogram of the Longmaxi Formation in well W201 in the southern Sichuan Basin.

southern and eastern Sichuan Basin, with a sedimentary thickness ranging from 99 m (in the Changning block) to 170 m (in the Luzhou block), which thins to less than 17 m (in the Weiyuan block) due to the overlap towards the central Sichuan uplift. None of the areas surrounding the central Sichuan uplift has been reported to find marginal facies and gravity flow sedimentary bodies, and the deposits are absent in the northern Sichuan Basin. This illustrates that the central Sichuan uplift may form an underwater uplift by connecting with the Hannan uplift (Fig. 3). SQ1 sequence is an organic-rich shale section having high gamma-ray value and middle–high resistivity, with GR values of 150–300 API, resistivity of 20–50 Ω·m, average calcareous content of 12%–18%, average clay content of 40.5%–43.0%, and average *TOC* of 1.7%–4.0% (Figs. 1 and 3 and Table 1). TST, the main shale gas production layer, is an organic-rich and silica-rich shale section dominated by thin to medium/thick-bedded siliceous shale, calcareous siliceous shale and carbonaceous shale assemblage interbedded with multiple laminated bentonites, recording the maximum transgression of Ordovician to Silurian. HST is generally an Aeronian Demirastrites zone, with the lithology of medium/thick-bedded silty shale and clay shale assemblage, medium to high GR values, and decreased organic matter abundance of 1%–2%, indicating the shallowing of water bodies.

SQ2 is the sequence from the middle-upper Aeronian to Telychian that contains five graptolite zones, i.e., *D. pectinatus-M. argenteus*, *Lituigraptus convolutus*, *Stimulograptus sedgwickii*, *Spirograptus guerichi* and *Spirograptus turiculatus*, and has a shorter sedimentary cycle than SQ1, representing the semi-deep water to shallow water sedimentary environment of Longmaxi Formation in the middle-late stage. As a result, a shale section of the middle-upper Aeronian is present in the Changning block, a section from middle-upper Aeronian to Telychian (Telychian-dominated) is present in the Weiyuan–Huaying block, and only the Telychian appears to be deposited in the northern Sichuan Basin. The maximum flooding surface is located at the peak of natural gamma-ray in upper Aeronian. The depocenter at that period is located within the southern Sichuan (Aeronian depocenter) and the northern Sichuan (Telychian depocenter) regions, with a thickness of 200–350 m and 150 m, respectively, and thins towards the central Sichuan uplift to less than 60 m (Fig. 3). This sequence is generally a shale section that is rich in clay mineral and lean in organic matter (Fig. 1 and Table 2). Regionally, the lithofacies vary greatly, with medium-thick to

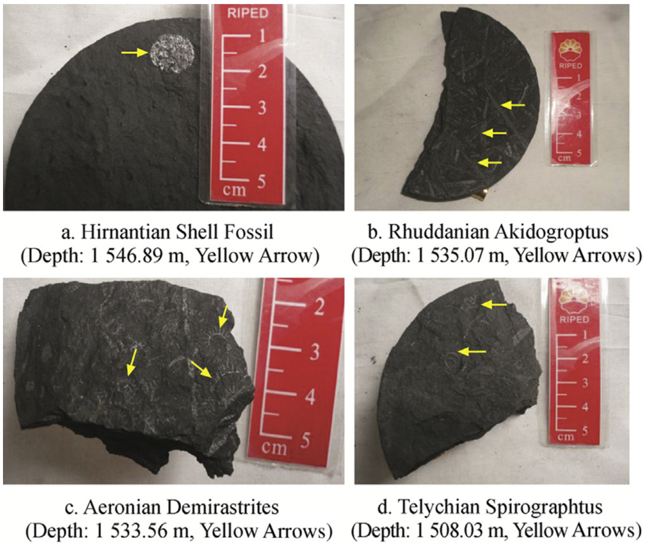

Fig. 2. Photos of typical paleontological fossils of the Wufeng–Longmaxi formations obtained from well W201 in the southern Sichuan Basin.

thick, gray black to gray calcareous & clay shale (clay content averages 47%, *TOC* averages 0.9% and R_t ranges from 10 to 1000 $\Omega \cdot$m) present in the Changning region and thick-bedded, dark gray to gray to grayish green clay shale (clay content averages 67%, *TOC* averages 0.2% and R_t ranges from 6 to 9 $\Omega \cdot$m) (Table 1) present in the Weiyuan and Huaying regions, suggesting that the central Sichuan paleo-uplift was generally submerged underwater and hence did not serve as provenance. This illustrates that sea-level fell significantly during the sedimentation period of SQ2, and that the depocenter moved towards the northwest, the Hannan paleo-uplift subsided and became a depocenter in Telychian stage. Lithofacies vary widely in both lateral and vertical directions but generally remain clay shale and mixed calcareous & clay shale. It is clear that, during the sedimentary evolution of the Longmaxi Formation, from the southern Sichuan to central Sichuan uplift, each of the system tracts shows evident overlap, the geologic age generally becomes younger, and the sedimentary thickness of SQ2 is commonly twice more than that of SQ1. This may suggest that, sea-level rises rapidly in early Rhuddanian, and then drops continually in late Rhuddanian–Telychian, and, as a consequence, the sedimentation rate is very low in the early stage but increases in the middle-late stage and the depocenter gradually moves towards the west.

2. Major marks of sedimentary facies

A number of studies related to the facies mark of the sedimentary environment by Liang Digang et al. are available for the marine strata in South China, and a unified criterion, comprising matrix fabrics, sedimentary structures, sand content, paleontology, special minerals and geochemical parameters, has been developed for dividing fine-grained sedimentary rocks

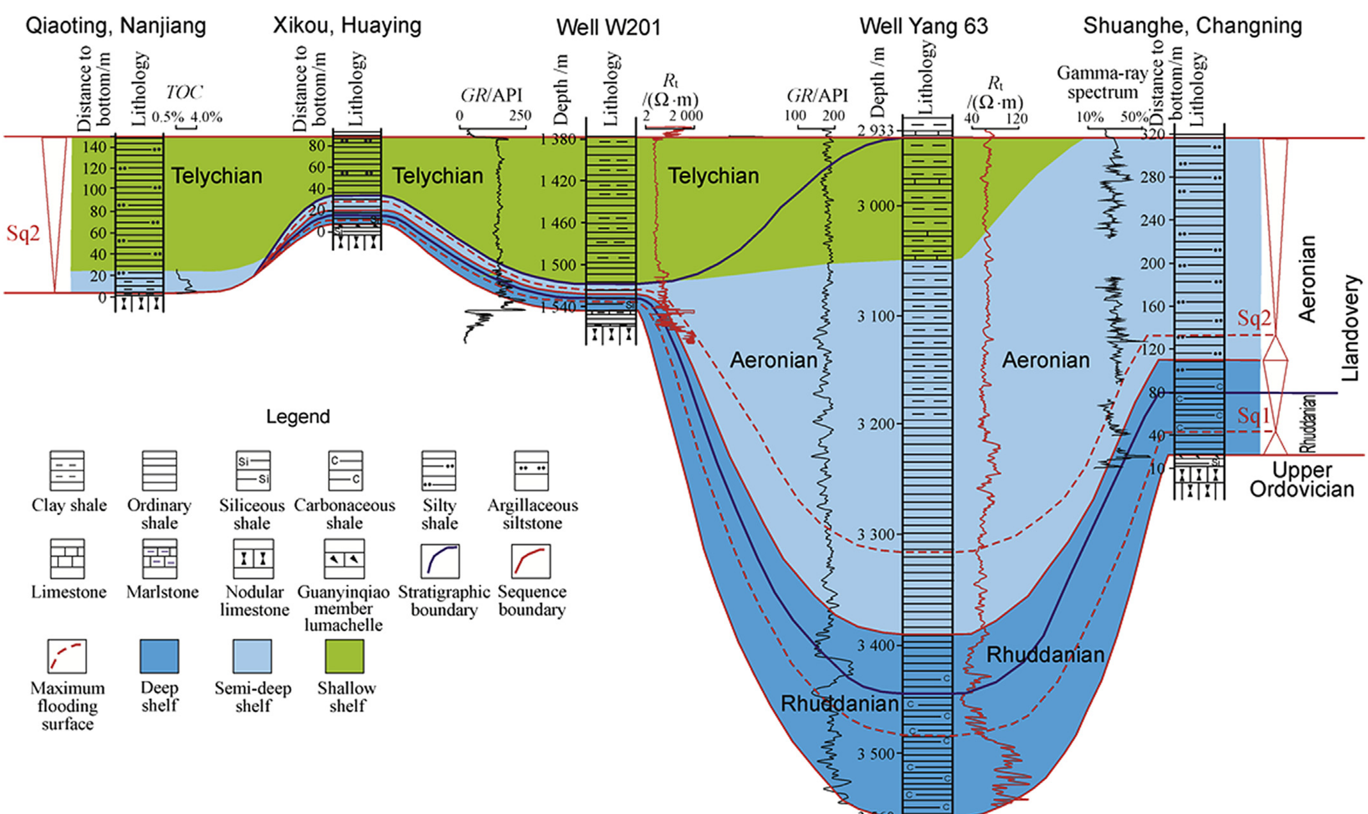

Fig. 3. Sequence framework of the Longmaxi Formation (Lower Llandovery) across the southern, central and northern Sichuan Basin.

Table 1
Main parameters of the Longmaxi Formation sequence in the Weiyuan and Changning regions.

Block	Third-order sequence	Thickness/m	Lithofacies assemblage	Main mineral content			TOC	Log response		Major sedimentary phenomenon
				Quartz + feldspar	Calcareous	Clay mineral		GR/API	Resistivity/(Ω·m)	
Weiyuan	SQ2	130	Dark gray shale at bottom, grayish green clay shale dominates the middle-upper part, intercalated with argillaceous siltstone, noncalcareous	28%–32% (30%)	0–5.0% (1.5%)	63%–71% (67%)	0.14%–1.25% (0.20%)	150	6–9	Horizontal bedding, with gravity flow deposits
	SQ1	17	Black siliceous shale, calcareous & siliceous shale, carbonaceous shale, with calcareous globoid, intercalated with multiple laminated bentonites	12%–69% (33%)	4.4%–46.5% (18.0%)	11.0%–73.0% (40.5%)	0.6%–6.4% (1.7%)	150–300	20–40	Horizontal bedding
Changning	SQ2	199	Silty shale, calcareous shale, with calcareous globoid, with carbonate turbidity current sedimentary body at upper part	22%–47% (29%)	11%–43% (24%)	30%–65% (47%)	0.5%–1.9% (0.9%)	100–150	10–1000	Horizontal bedding, with gravity flow deposits
	SQ1	99	Black siliceous shale, calcareous & siliceous shale, carbonaceous shale, with calcareous globoid, intercalated with multiple laminated bentonites	29%–70% (44%)	4.7%–34.0% (12.0%)	15%–64% (43%)	1.2%–8.4% (4.0%)	>150	20–50	Horizontal bedding

Note: Value in parentheses is the average.

[2,16,19–25]. The authors, based on previous study results, added the calcareous content and log response to that criterion, and, according to the regional sedimentary characteristics of the Longmaxi Formation, created a criterion for dividing the sedimentary facies of the Lower Silurian shale stratum (Table 2). Due to the limitation of the length, only the calcareous content was discussed in this paper.

2.1. Calcareous content

The Longmaxi Formation was formed in a semi-closed shelf environment on the edge of the Yangtze platform [2,14–16], so the calcareous content of rocks undoubtedly provides a critical index that reflects the water-depth and sedimentary environment. It is usually considered that, shallow platform provides a carbonate sedimentary zone, with calcareous content commonly exceeding 50%; shelf area provides a calcareous shale sedimentary zone, with calcareous content of less than 50% which would decrease as water-depth increases (inner shelf area ranges from 25% to 50% and outer shelf-continental slope area ranges from 10% to 25%); and the deep-sea basin is dominated by clay shale sedimentation because its water is deep enough to submerge the carbonate compensation level, with calcareous content less than 10%. The authors developed the relationship between calcareous content and organic carbon content of the Longmaxi Formation by utilizing the two sections of Changxi Shuanghe and Qijiang Guanyinqiao and drilling data. This may provide a basic understanding of relationship between lithofacies and sedimentary environment of marine shale (Fig. 4).

(1) Clay shale: with a calcareous content of less than 5%; pure quality; fine grains (grain size of 5–40 μm); mainly deposited in deep-water basins, with *TOC* ranging from 0.40% to 1.85% (average: 1%), or on shallow argillaceous shelf, with *TOC* of less than 0.5%.
(2) Calciferous shale: with a calcareous content ranging from 5% to 25%; with horizontal lamination; containing flocculated globule and biologic skeleton grains, with grain size ranging in 9–75 μm; deposited in relatively quiet deep shelf areas; organically-rich, with *TOC* ranging from 0.5% to 8.4%.
(3) Calcareous shale: with a calcareous content ranging from 25% to 50%; silty shale-like; containing sand-sized grains, flocculated globule and biologic skeleton grains, with grain size ranging in 12–68 μm; mainly deposited in deep to semi-deep continental areas; organically-rich, with *TOC* ranging from 0.2% to 4.1%.
(4) Argillaceous limestone: with a calcareous content ranging from 50% to 75%; mainly deposited on calcareous shallow shelf-platform areas; lack of organic-rich shale, with *TOC* ranging from 0.14% to 0.98% and reaching 1% locally.
(5) Limestone: with a calcareous content exceeding 75%; mainly deposited in platform areas; organic-lean, with *TOC* ranging from 0.1% to 0.35%. The organic matter abundance of the Longmaxi Formation is closely related

Table 2
Criterion of sedimentary facies division for the Longmaxi Formation in Sichuan Basin and its peripheral areas.

Subfacies	Deep shelf		Semi-deep shelf		Shallow shelf		Shelf edge (shoreland)	
	Calciferous shelf	Argillaceous shelf	Calcareous shelf	Argillaceous shelf	Calcareous shelf	(Sandy) argillaceous Shelf	Limy/dolomitic shoreland	Sandy & argillaceous shoreland
Water depth	100–200 m (beneath the basal surface of *Demirastrites* living zone)		60–100 m (maximum storm wave base to basal surface of *Demirastrites* living zone)		20–60 m (normal wave base to maximum storm wave base)		<20 m (supratidal to intertidal belt)	
Lithologic assemblage	Assemblage of calciferous siliceous rock, siliceous shale and clay siliceous shale	Siliceous shale and clay siliceous shale	(Dark) gray clay & calcareous shale and calcareous shale	Clay shale	(Light) gray calcareous shale and marlstone, with sheet sand of storm origin and laminated limestone deposited locally	Grayish green to yellow green clay shale, with spatulate weathered outcrops and siltstone developed locally	Limestone and dolomite	Assemblage of grayish green to yellow green sandstone and mudstone
Matrix fabric	Flocculated globule and biologic skeleton grains, mostly rounded spherulite, with grain size of 9–75 μm		Sand-sized grains, flocculated globule and biologic skeleton grains, mostly globular and subangular, with grain size of 12–68 μm, dispersed in clay		Sand-sized grains dominate with grain size of 5–4 0 μm, e.g., quartz, feldspar and calcite, few flocculated globule and biologic skeleton, mostly subangular		/	
Sedimentary structure	Horizontal bedding, uniform bedding, with gravity flow deposits		Horizontal bedding and uniform bedding, with gravity flow deposits		Ripple bedding, wavy bedding and cross bedding		Bedded and massive	Cross bedding
Paleontology	Abundant *Akidogroptu*s and *Climacograptus*, limited in size, with microfossils (e.g., foraminifer, spongy spicule and radiolarian) and hornstone		Rastrites and Spirographtus occur, abundant Orthograptus, hornstone		Petalolithus, with assemblage of benthic fauna (e.g., Brachiopoda and coral)		None	None
Calcareous content	10%–25%	<10%	25%–40%	<10%	40%–70%	<10% (mostly <5%)	>70%	<10%
Special mineral	Abundant pyrite		Pyrite					
GR/API	150–300		120–150	120–160	<120	50–150	<70	<100
Resistivity/(Ω·m)	20–60	10–70	20–200	10–20	200–700	<10		
TOC	>1.5%		0.5%–1.5%		<0.5%		<0.2%	
Typical region	Southern Sichuan –eastern Yunnan	Central Sichuan, eastern Sichuan –western Hubei, northern Sichuan and middle Yangtze	Southern Sichuan –eastern Yunnan	Central Sichuan, eastern Sichuan –western Hubei, northern Sichuan and middle Yangtze	Southern Sichuan –eastern Yunnan	Northern Sichuan –central Sichuan –eastern Sichuan	Eastern Yunnan	Southeast Chongqing –northern Guizhou

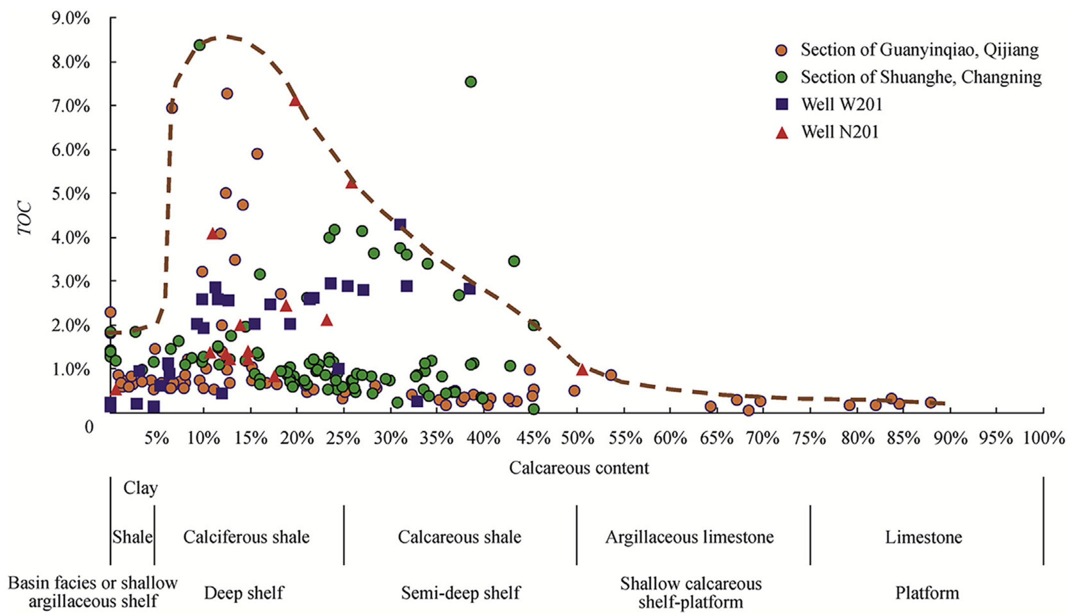

Fig. 4. Diagram of *TOC* vs. calcareous content of the Longmaxi Formation in the southern Sichuan Basin.

to calciferous shale facies and calcareous shale facies, i.e., organic-rich shale is dominated by calciferous shale deposited in deep shelf areas and calcareous shale deposited in semi-deep to deep continental areas, and is absent in shallow shelf-platform environment and deep-water basins where calcareous content is less than 5%. This suggests that, organic-rich marine shale is deposited primarily in deep shelf areas with a calcareous content ranging from 5% to 25% and secondly in semi-deep shelf areas with a calcareous content ranging from 25% to 50%.

2.2. Sedimentary microfacies division

Based on lithofacies, sedimentary structures, paleontology, paleo-water-depth, calcareous content, log response and geochemical indexes, the author have identified a total of four subfacies and eight microfacies (Table 2) of the Longmaxi Formation in the upper Yangtze region.

2.2.1. Deep shelf facies

In an area with a water depth ranging from 100 m to 200 m (i.e., beneath the basal surface of *Demirastrites* living zone), organic- and silica-rich deposits formed (with *TOC* and siliceous content commonly exceeding 1.5% and 40%, respectively) because *Akidogroptus*, *Climacograptus* and skotoplankton (e.g., radiolarian, foraminifer and spongy spicule) boom. Two types of microfacies by far have been identified: deep calcareous shelf and deep argillaceous shelf. Deep calcareous shelf mainly contains the assemblage of calcareous & siliceous shale, siliceous shale and clay & siliceous shale, which is distributed in the southern Sichuan-eastern Yunnan regions, with common horizontal bedding and uniform bedding, gravity flow sediments deposited locally, calcareous content ranging from 10% to 25% and resistivity of 20–60 Ω·m. Deep argillaceous shelf contains the assemblage of siliceous shale and clay & siliceous shale, which is mainly distributed in the central Sichuan, eastern Sichuan-western Hubei, northern Sichuan and middle Yangtze regions, with calcareous content of less than 10%, and resistivity mostly ranging between 10 and 70 Ω·m.

2.2.2. Semi-deep shelf facies

In an area with a water depth ranging from 60 m to 100 m (maximum storm wave base to basal surface of *Demirastrites* living zone), abundant *Rastrites*, *Spirographtus* and *Monograptus*, and hornstone developed with *TOC* ranging from 0.5% to 1.5%. Two types of microfacies have been identified: semi-deep calcareous shelf and semi-deep argillaceous shelf. Semi-deep calcareous shelf contains the assemblage of (dark) gray clay & calcareous shale and calcareous shale, which is mainly distributed in the southern Sichuan-eastern Yunnan regions, with horizontal bedding and uniform bedding, gravity flow sediments deposited locally, calcareous content ranging from 25% to 40% and resistivity of 20–200 Ω·m. Semi-deep argillaceous shelf predominately contains clay shale deposits, which is mainly distributed in the eastern Sichuan Basin, the northern part of the southern and northern Sichuan Basin, with calcareous content of less than 10%, clay content exceeding 50% and resistivity ranging between 10 and 20 Ω·m.

2.2.3. Shallow shelf facies

In an area with a water depth ranging from 20 m to 60 m (normal wave base to maximum storm wave base), *Petalolithus* with simple-structure and benthic fauna (e.g., brachiopoda and coral) assemblage developed with *TOC* of less than 0.5%. Two types of microfacies have been identified: shallow calcareous shelf and shallow (sandy) argillaceous shelf. Shallow calcareous shelf is predominated by (light) gray calcareous shale and marlstone, which is mainly distributed in the southern Sichuan and eastern Yunnan regions, with sheet sand of storm origin and limestone lamina deposited locally, calcareous content ranging from 40% to 70% and resistivity of 200–700 Ω·m. Shallow (sandy) argillaceous shelf mainly contains grayish green, yellow green clay shale deposits interbedded with siltstone lamina, which are distributed widely in the central Sichuan, eastern Sichuan-western Hubei, northern Sichuan and middle Yangtz regions, with ripple bedding, wavy bedding and cross bedding, calcareous content of less than 10% (mostly less than 5%), clay content exceeding 50% and resistivity of less than 10 Ω·m.

2.2.4. Shelf edge (shoreland) facies

In an area with a water depth of commonly less than 20 m (supratidal to intertidal belt), this type of facies has a *TOC* of less than 0.2% and can be divided into two microfacies: limy/dolomitic shoreland and sandy & argillaceous shoreland. Limy/dolomitic shoreland microfacies predominately contains the assemblage of bedded or massive marlstone, dolomite and calcareous shale, which was poorly preserved and speculated to crop out in the eastern Yunnan region. Sandy & argillaceous shoreland microfacies mainly contains grayish green to yellow green mudstone, argillaceous siltstone and siltstone, which existed locally in the southeast Chongqing–northern Guizhou regions.

3. Sedimentary environment and evolution characteristics of the Longmaxi Formation

Based on the criterion for facies division described above, sea-level change and ocean current effect in Sichuan Basin and its peripheral areas, the authors conducted sequence correlation and sedimentary microfacies study on 55 data points (37 sections and 18 exploration wells) from the middle and upper Yangtze region. Moreover, the authors mapped the sedimentary facies of SQ1 and SQ2 to disclose the sedimentary characteristics of the Longmaxi Formation and their control action on black shale (Figs. 5 and 6).

3.1. Early Rhuddanian–Aeronian (SQ1 period)

During this period, the central Guizhou uplift rose to form land and became a part of the Jiangnan-Xuefeng paleo-land [2,16], and the continually uplifted but still submerged central Sichuan uplift extended into the Hannan region. As a result of climate warming and global ice sheet melting, sea level rose rapidly to result in the maximum transgression during the Silurian, forming a broad semi-closed deep-water bay that covered an area of over 10×10^4 km^2. This bay, with a mouth to the north, a water depth exceeding 100 m, a non-compensation state, inactive ocean current and low sedimentation rate [24], provides enough accommodation space for the large-scale sedimentation of black shale. The margin of the depression is generally a shallow water zone, with features as follows: (1) an underwater uplift is developed in the northern Sichuan Basin, which has not yet received the shale sedimentation; (2) the shallow argillaceous shelf zone exists in the northeastern margin of the central Sichuan underwater uplift and along the northwestern margin of Xuefeng paleo-land – Yichang; and (3) shallow calcareous shelf and shelf edge facies are seen in the northern margin of the central Guizhou uplift (in Fig. 5).

The deep water facies can be divided into two parts from north to south along Well W201 – Well Zh 101 – Well Lin 7 – Sanquan – Xiabei – Fengle, due to the control of paleography and provenance. The southern part, controlled by the central Guizhou carbonate paleo-land, is generally a semi-deep to deep calciferous sedimentary environment, with a calcareous content ranging from 10% to 25%, resistivity of 20–60 Ω·m, maximum *TOC* exceeding 10% and the depocenter located along Luzhou–Changning. The northern-northeastern part, controlled by the Kangdian paleo-land and Jiangnan-Xuefeng paleo-land, is generally a semi-deep to deep argillaceous shelf zone, with a clay mineral content ranging from 30% to 50%, a calcareous content of less than 10%, a resistivity of 5–50 Ω·m, maximum *TOC* of approximately 6% and the depocenter located along Daozhen–-Shizhu–Wanzhou. Based on clay mineral (terrigenous matter) content and *TOC*, the deep-water zone in the eastern Sichuan-western Hubei region is speculated to receive more terrigenous matters and has a shallower water body than the southern Sichuan Basin due to its proximity to the Xuefeng provenance. Controlled by the depocenter, black shale ($TOC > 1.0\%$) is mainly distributed in the southern Sichuan (30–170 m) and eastern Sichuan-western Hubei (30–110 m) regions. In particular, black shale is thinner in the western Hubei region than in the eastern Sichuan and southern Sichuan Basin due to the absence of middle and lower strata of Rhuddanian in the Longmaxi Formation [26] resulted from the uplift in Yichang.

3.2. Middle-late Aeronian–Telychian (SQ2 period)

As sea level dropped and ocean receded towards the north [2,19–22], the depocenter moved to the central and northern Sichuan Basin. The central Sichuan uplift, although submerged, was more limited in area towards the south. The shallow bay became the main part of the study area, and the deep-water zone was only distributed locally in the southern, northern and eastern Sichuan Basin, with a shallowing water depth of 100 m (in Fig. 6). This period witnessed a transition from deep-water facies to semi-deep shelf, including a semi-deep calcareous shelf (calcareous content of greater than 25%) seen in Luzhou–Changning and a semi-deep argillaceous shelf (calcareous content of less than 10%) seen in Zigong–Longchang–Chongqing, surrounded by the shallow shelf zones. The deep-water zone in the eastern Sichuan Basin shrinks considerably, with semi-deep shelf seen locally in Daozhen-Wulong and Fuling-Shizhu regions and sheet sand deposited broadly over the shallow shelf zone in the east of Qianjiang–Lichuan. The northern Sichuan Basin began to receive deposits in Telychian stage, with deep-water facies seen only in the Zhenba region. The shallowing of water

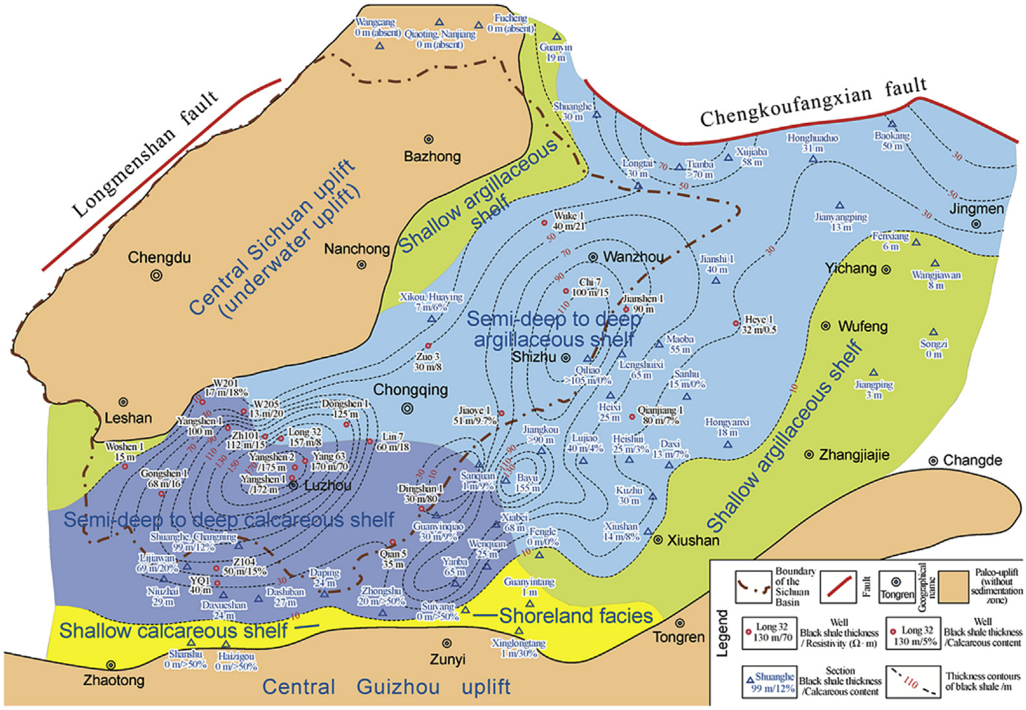

Fig. 5. Sedimentary facies of the Longmaxi Formation in Sichuan Basin and its peripheral areas at early stage (SQ1).

bodies and variation of sedimentary frameworks resulted in a significant decrease in the scale of black shale, which is distributed primarily in the southern Sichuan Basin (30–90 m), and secondly in the northern Sichuan (10–50 m) and eastern Sichuan (10–30 m) regions.

Black shale was deposited during the Rhuddanian, Aeronian and Telychian stages, and the organic-rich deep-water facies shale was formed predominately in early Rhuddanian–Aeronian. In the southern Sichuan depression where a continuous and stable (semi-)deep shelf depocenter for the upper Yangtze region is located, black shale is 60–260 m thick, of which the deep-water facies shale is 30–170 m and considered to be the most perspective area of shale gas. In the southern Sichuan depression where the deep-water

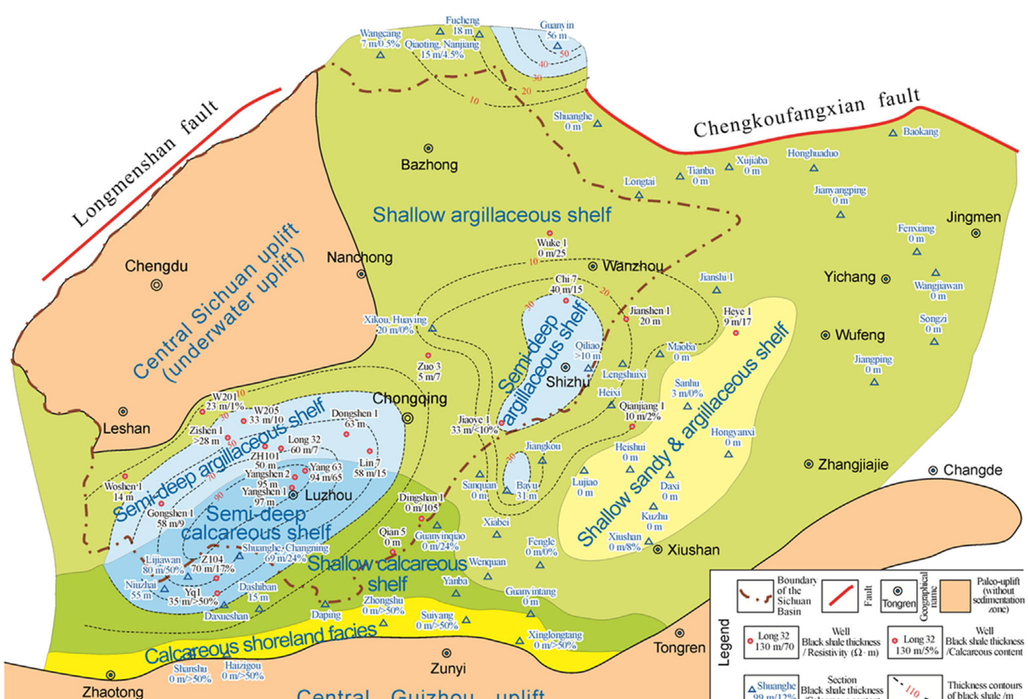

Fig. 6. Sedimentary facies of the Longmaxi Formation in Sichuan Basin and its peripheral areas at later stage (SQ2).

depocenter for the Rhuddanian and Aeronian stages is located, the deep-water domain basically vanished due to later-stage uplift, and the black shale is 40–140 m thick, of which the deep-water facies shale is 30–110 m thick and considered to be a perspective province of shale gas. The northern Sichuan Basin where deep-water domain was formed in a later stage has a much less exploration potential of shale gas than the southern and eastern Sichuan Basin because of the limited distribution and scale of the black shale. Given that the western Hubei region has developed much less deep-water facies shale than the southern and eastern but more than the northern Sichuan Basin, this region is judged to be between these regions in shale gas exploration potential.

4. Conclusions

(1) With regional diachronism of the top and the bottom, the Longmaxi Formation can be divided into two third-order sequences (SQ1 and SQ2) by using marker beds such as Hirnantian shell facies bed and Aeronian *Demirastrites* zone.

(2) A total of eight microfacies can be identified in the Longmaxi Formation: deep calcareous shelf, deep argillaceous shelf, semi-deep calcareous shelf, semi-deep argillaceous shelf, shallow calcareous shelf, shallow (sandy) argillaceous shelf, limy/dolomitic shoreland and sandy & argillaceous shoreland. Organic-rich shale is mainly developed in deep shelf zone. The central Sichuan paleo-uplift is a continuous underwater uplift.

(3) Organic- & silica-rich shale was deposited predominately in SQ1 period. As global sea-level rose rapidly, two deep shelf zones were formed in the southern Sichuan-northern Guizhou and eastern Sichuan-western Hubei regions, with 30–170 m thick black shale deposited. Deep calcareous shelf deposits are present in the southern part of the southern Sichuan Basin, and deep argillaceous shelf deposits exist in the northern part of the southern and eastern Sichuan Basin.

(4) The depocenter moved towards the northern Sichuan Basin in response to the shallowing of sedimentary water bodies during SQ2 period, resulting in the younger Longmaxi Formation black shale in the northern Sichuan Basin than that in the southern and eastern Sichuan Basin. The lithofacies are dominated by clay shale and calcareous & clay shale.

(5) The major shale gas production layer of the Longmaxi Formation was deposited in SQ1 period, and the deep-water shelf center in the southern and eastern Sichuan Basin is the most perspective play of shale gas exploration in the Longmaxi Formation shale. The deep-water domain in the northern Sichuan Basin was formed in SQ2 Highstand System Tract, with very limited black shale deposited. Thus, it carries a less exploration potential of shale gas than the southern and eastern Sichuan Basin. The Longmaxi Formation in the western Hubei region is judged to be between the southern, eastern and northern Sichuan Basin in shale gas exploration potential.

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