Organic Matter Characteristics of Silurian Marine Mudstone and Factors to Shale Gas Accumulation in Sichuan Basin, China*

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Abstract

Shale gas is one kind of unconventional gas resource stored in organic-rich shales and mudstones. The global endowment of shale gas resource is 456 trillion cubic meters, mainly distributed in North America, Asia, Europe and Africa. It is assumed that nearly 40% of this endowment would be economically recoverable. Recent preliminary studies show that shale gas reserves in the Cambrian Qiongzhusi Formation and Silurian Longmaxi Formation in Southern Sichuan Basin, China are about 6.8-8.5 trillion cubic meters.

In order to examine the vertical changes in organic matter content of Silurian Longmaxi Formation marine shale, two fresh outcrop profiles located at the southwest margin and south margin of the Southern Sichuan Basin were selected for our study. The Shuanghe Town outcrop is an East-West trending anticline, comprised of black or dark gray graptolite shale, carbonaceous shale, siliceous shale and silty shale and argillaceous from bottom to top. The Bowangshan Town outcrop is northward-inclined strata and the lithofacies is consistent with Shuanghe Town outcrop.

TOC content, Rock-Eval pyrolysis and petrological characterization of 124 Shale samples from the two outcrops were conducted. The results show that TOC content at the bottom of the Longmaxi Formation ranges from 3.04% to 7.28%, and the thickness of high TOC content interval is about 30m. The value of Ro is more than 2.5%, indicating high to over thermal maturation favorable for gas generation. X-ray diffraction analysis shows that the brittle minerals content is about 37.1%-71.2%, in which quartz content is 24.3%-43.5%, potassium feldspar and plagioclase content is 4.3%-10.8%, calcite content is 8.5%-16.9%, clay mineral content is 37.4%-48.3%. Clay minerals are dominated by stable minerals, lack of swelling clay minerals like montmorillonite, in which illite content is 52.0%-80.0%, chlorite content 10.0%-20.0%, and kaolinite content 0-6.0%. Natural fractures, cracks and pores developed in the Longmaxi Formation provide spaces for shale gas storage. The vertical variation in TOC content in Longmaxi Formation reflects regional transgression, deepwater reducing environment and slow sedimentation rate. As a result, the lower part of Silurian marine mudstones in the Sichuan basin is a favorable target for shale gas exploration.

Organic Matter Characteristics of Silurian Marine Mudstone and Factors to Shale Gas Accumulation in Sichuan Basin, China

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Outline

- Distribution of shale gas resources
- Geology of Sichuan Basin
- Total organic carbon (TOC)
- Thermal maturity（Ro）
- Mineral composition
- Gas content
- Pores and fractures
- Conclusions

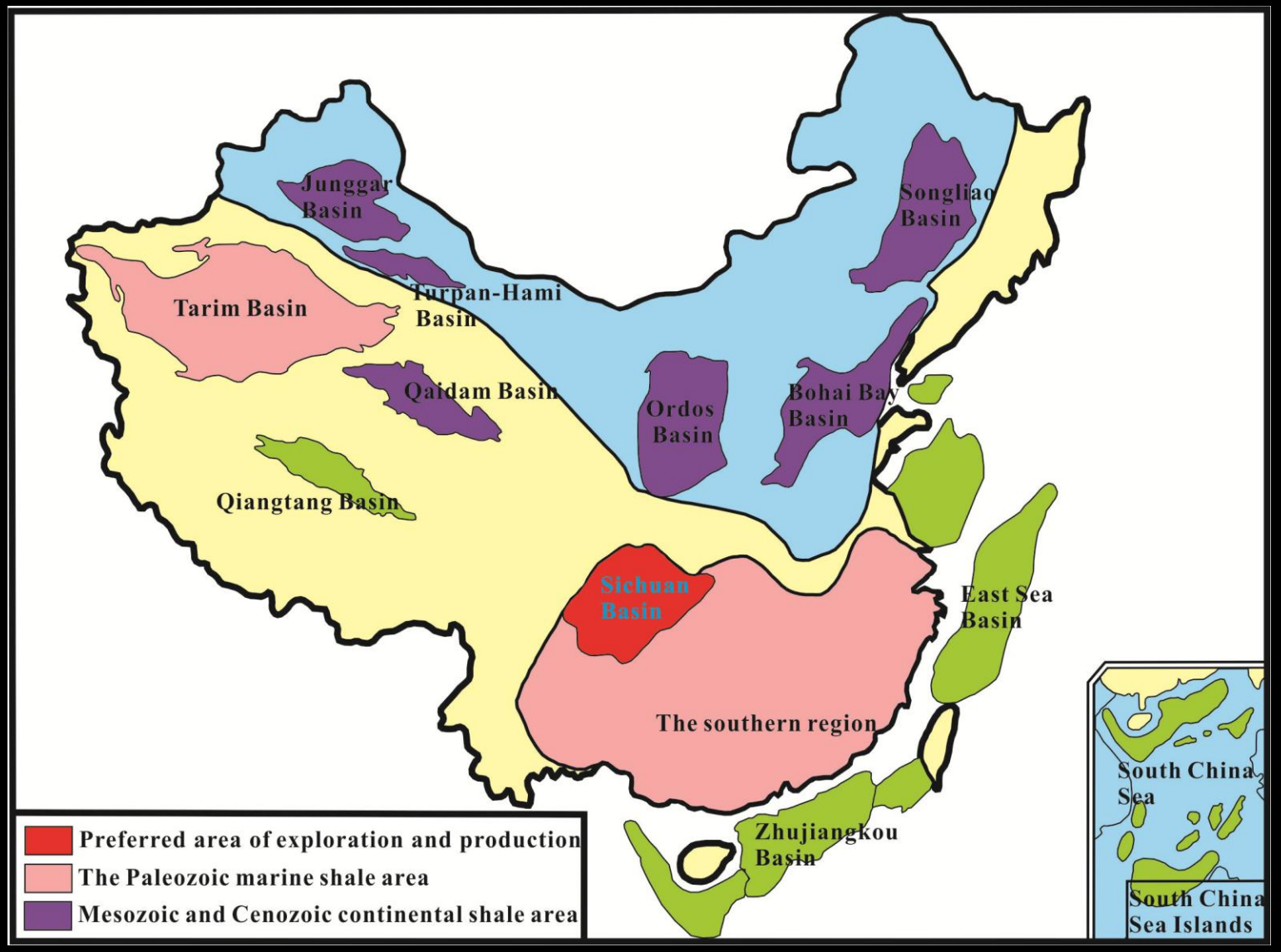
Global Shale Gas Resources

The global shale gas resources reach $456\times10^{12}m^3$, and technically recoverable resources amount to 40% ($187\times10^{12}m^3$), $36\times10^{12}m^3$ in China

Country/region	Technically recoverable resources(Tcf)
Canada & Mexico	30.3
USA	24.4
North America Total	54.7
7 countries in South America	34.7
Europe（except the Russian Federation）	17.7
Africa	29.5
China, India, Pakistan	39.8 (China,36)
Australia	11.2
total	187.4

According by EIA, 2011

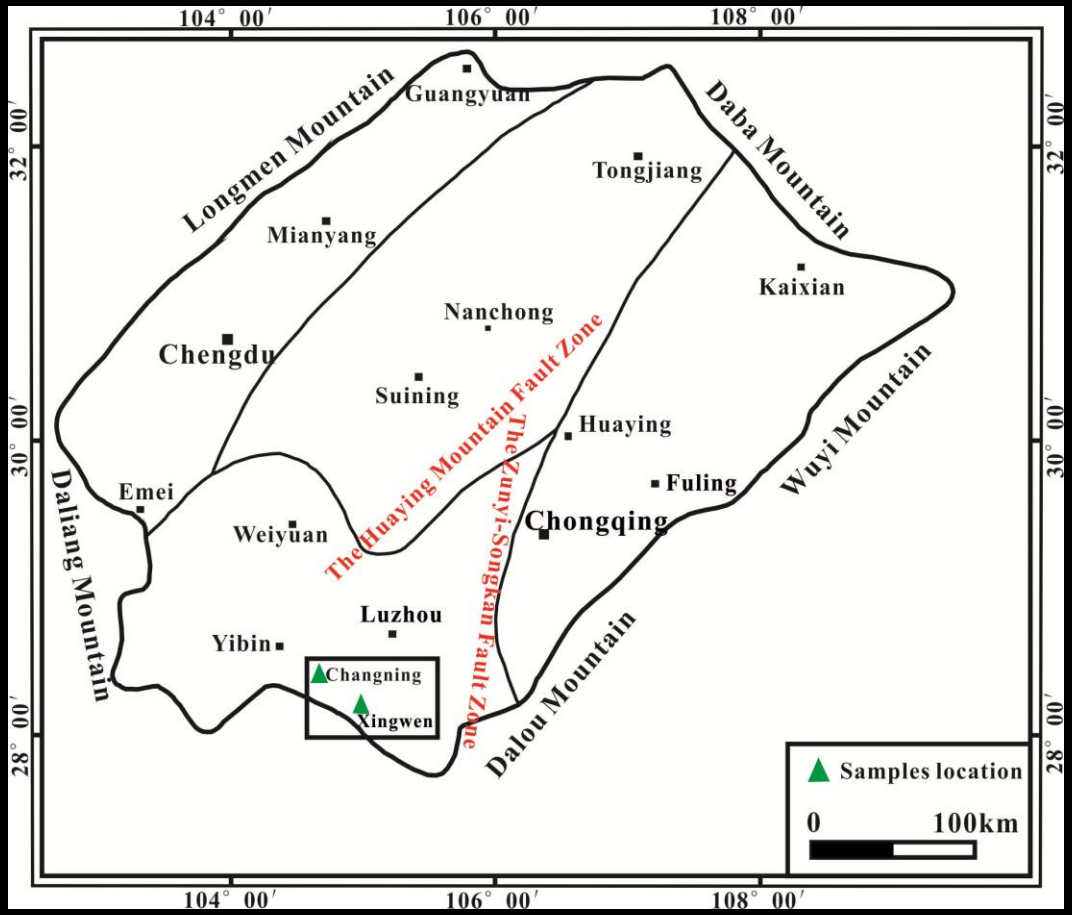
Shale Gas Potential Resources in China



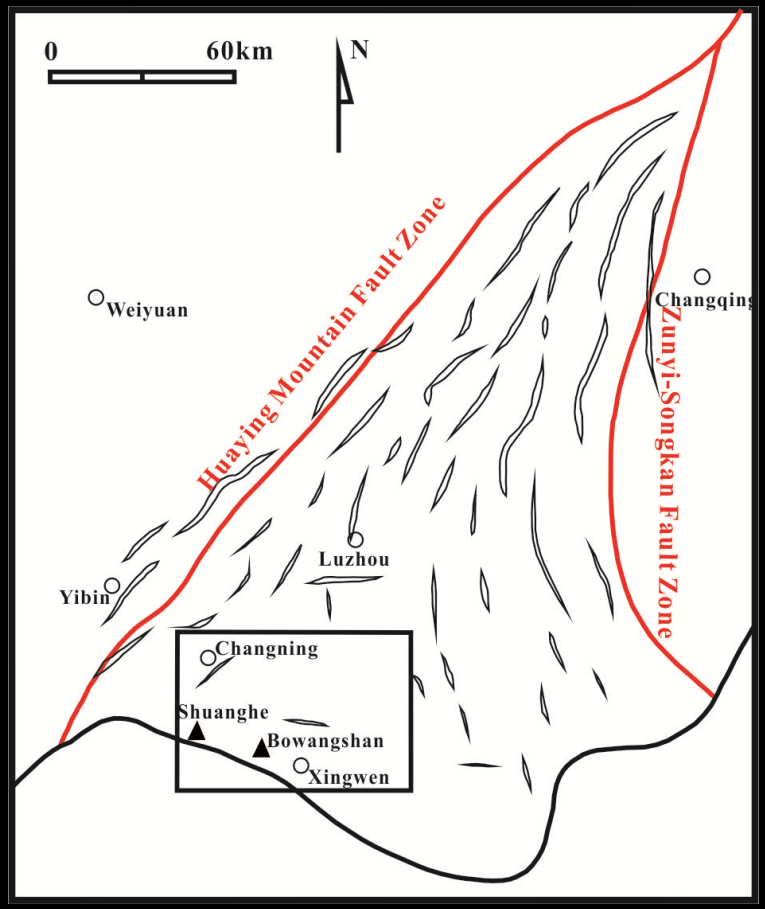
According by Zhang Jinchuan, et al. 2007

Structural Elements in Sichuan Basin

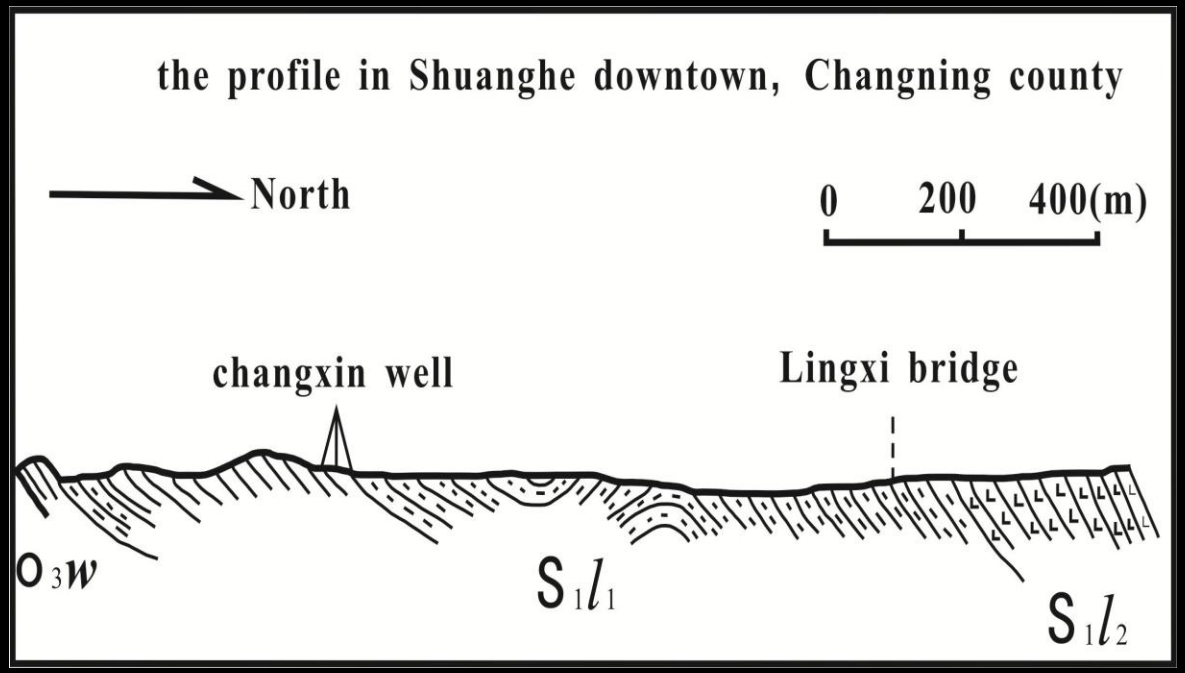
Southern Sichuan Fold Area



The Southern Edge of Fold Area

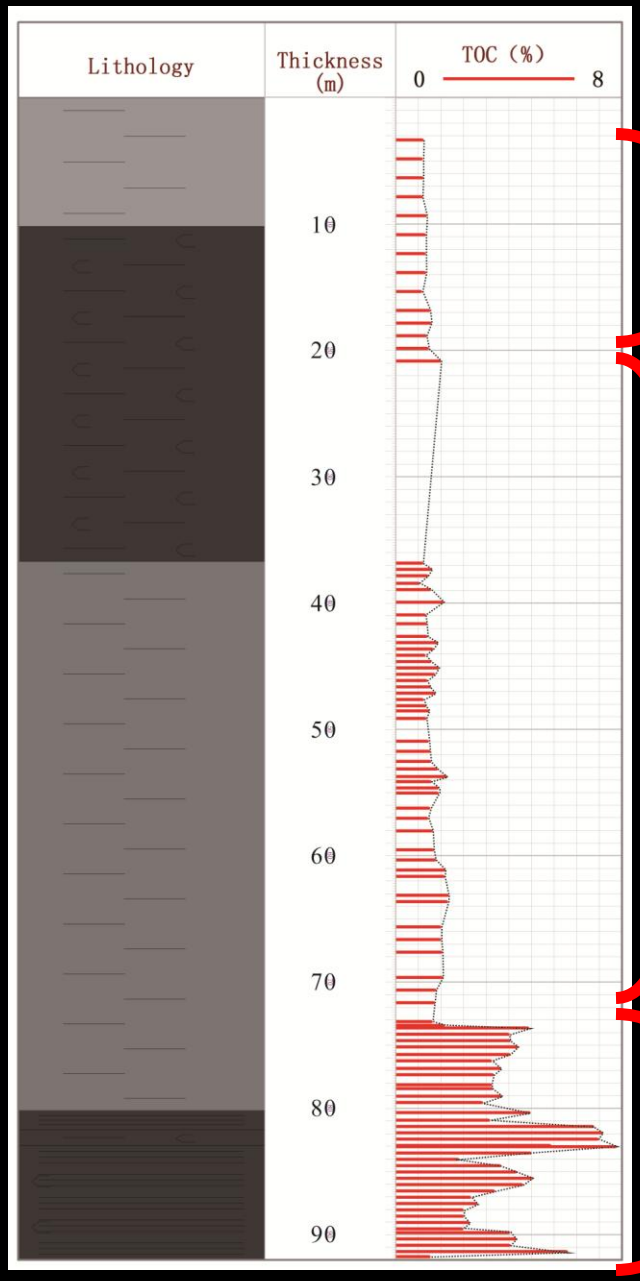


The Outcrop of Silurian Longmaxi Fm. Marine Shale in Shuanghe Town, Changning



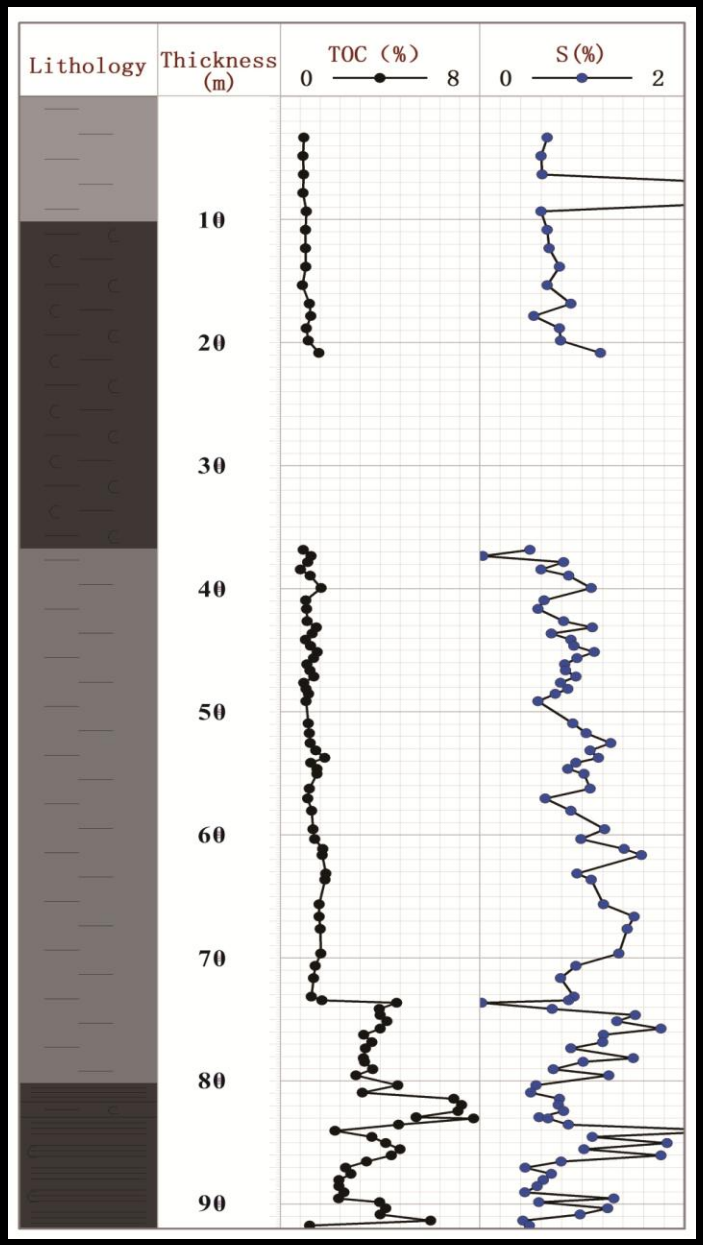
- black or dark gray graptolite shale, carbonaceous shale, siliceous shale and argillaceous silty shale developed from bottom to top.
- from bottom to top, is getting coarser in particle size and lighter in color.

The Vertical Change of Organic Matter Content



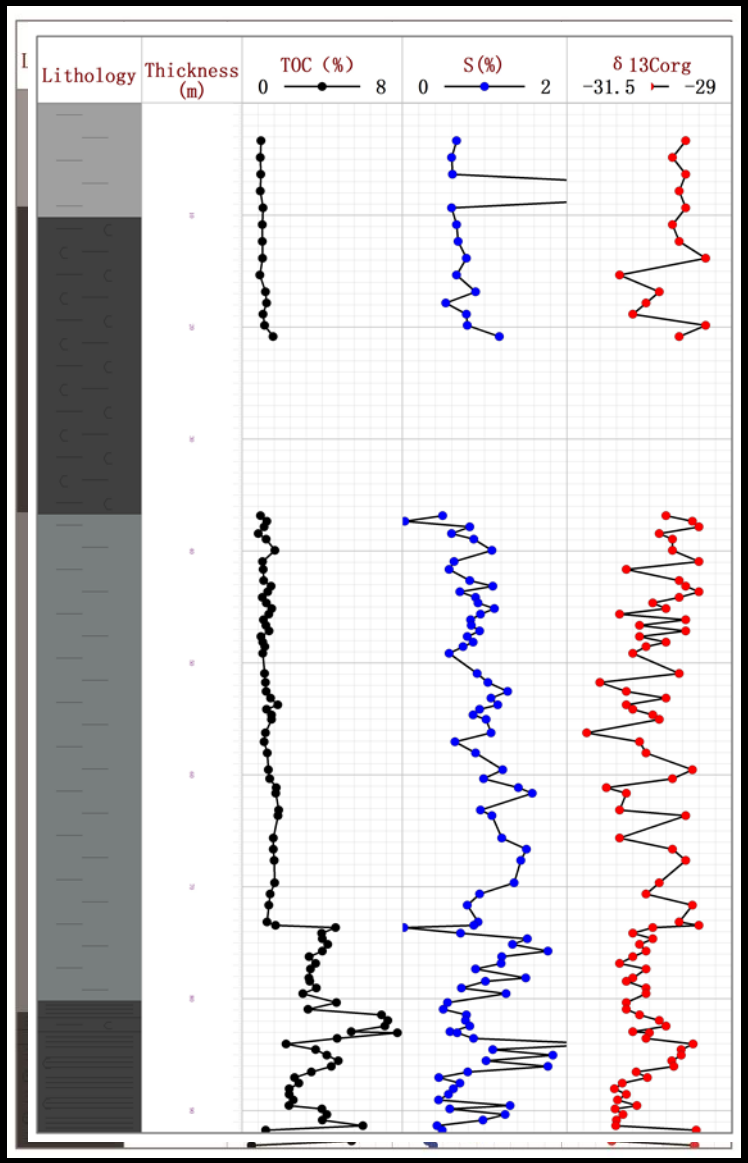
- TOC content stabilized at about 1%
- TOC value decreases to 1.83%-0.81% in this interval, and the thickness is 55m
- TOC content is high in this interval. (2.2%～7.28%), and the thickness is ~ 20m.

The Vertical Change in Sulfur Content



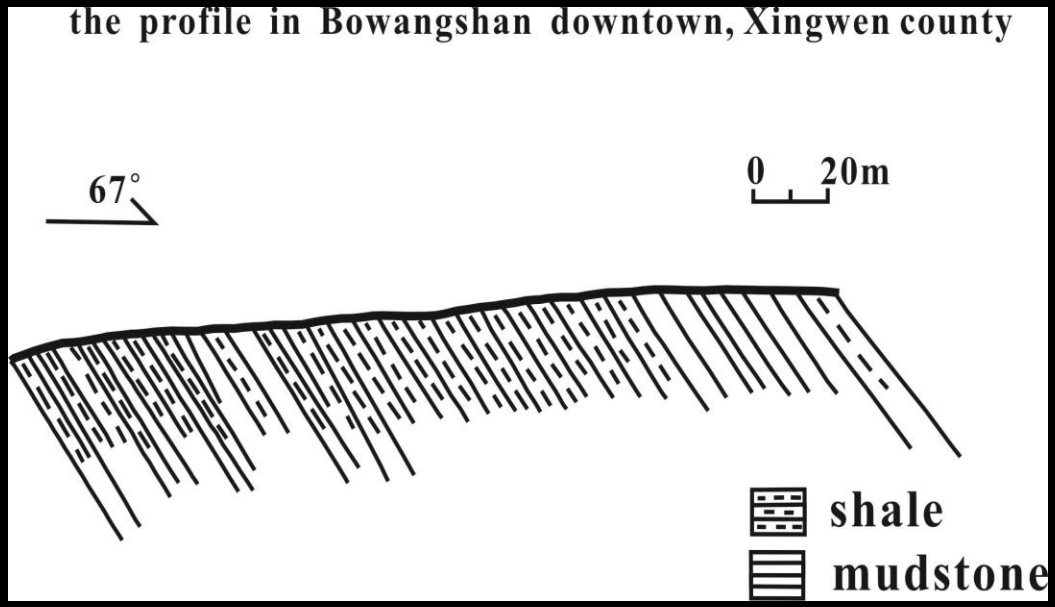
- The sulfur content is in the range of 0.02% to 4.69% with an average of 0.95%.
- The sulfur content is high and stable, in the 20m interval at the bottom of this profile. Sulfur content continuously increased in the middle 10m interval. The sulfur content is gradually reduced and stabilized in the upper interval.
- It reflects a transition process of depositional environment from the deep water shelf to shallow shelf.

The Vertical Changes in Organic Matter Carbon Isotope



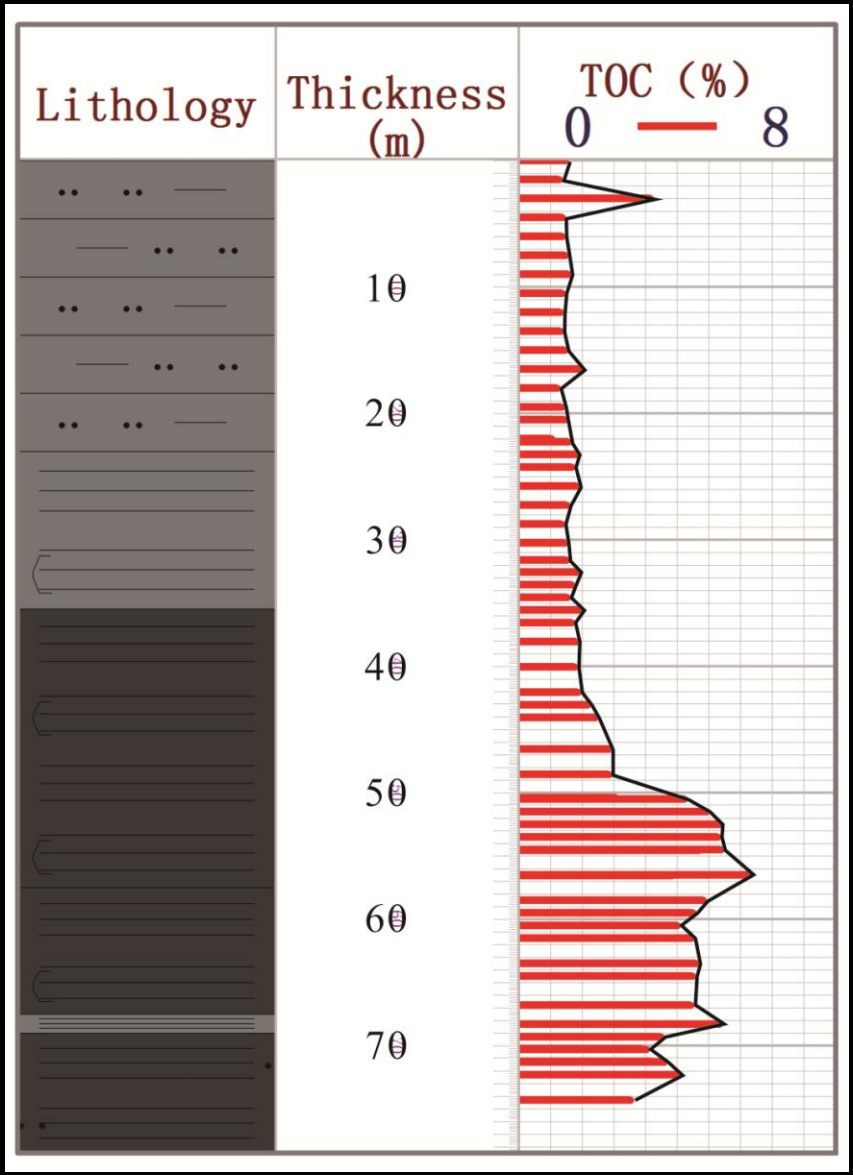
- The $\delta^{13}C_{org}$ value of the Longmaxi shale is from -31.2‰ to -29.4‰ with an average of -30.1‰. It indicate that organic matter is type - Ⅰ and Ⅱ dominated.
- the $\delta^{13}C_{org}$ value is lighter in the 20m interval at the bottom. And it gradually becomes heavy from the bottom to the top in Longmaxi Fm.
- The vertical changes of $\delta^{13}C_{org}$ value reflects regional regression and increase of oxicity in water.

The Outcrop Of Silurian Longmaxi Shale in Bowangshan Town, Xingwen



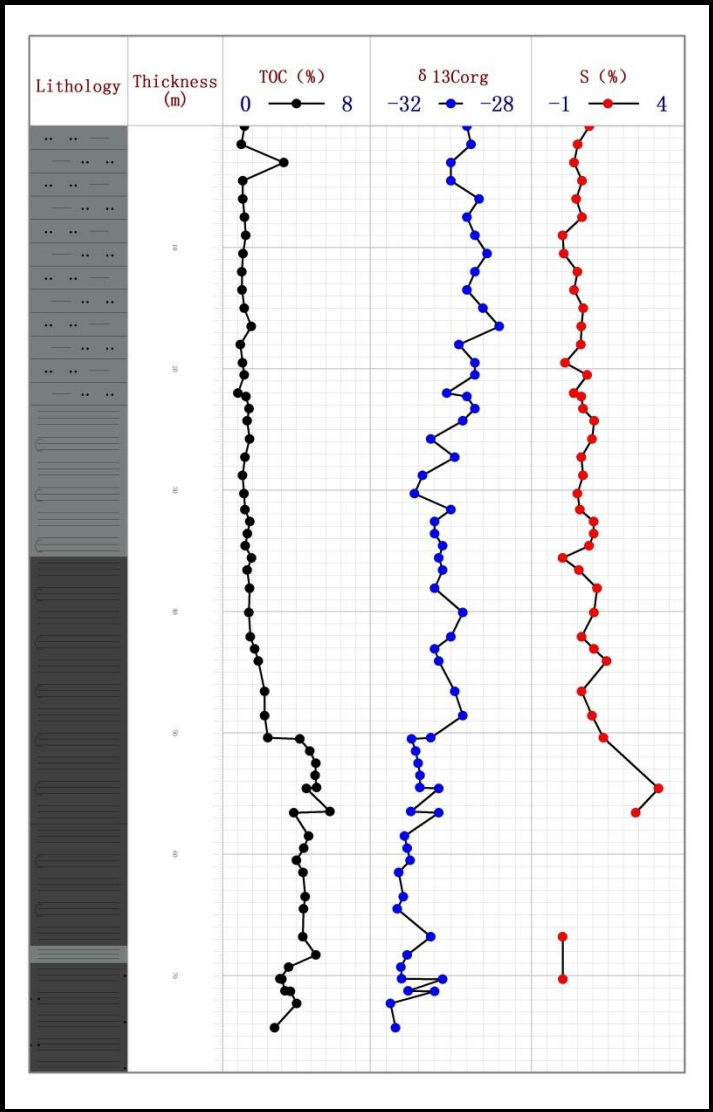
Bowangshan Town profile is a nearly north-south profile, whose lithology is well consistent with Shuanghe town profile.

The Vertical Change of Organic Matter Content



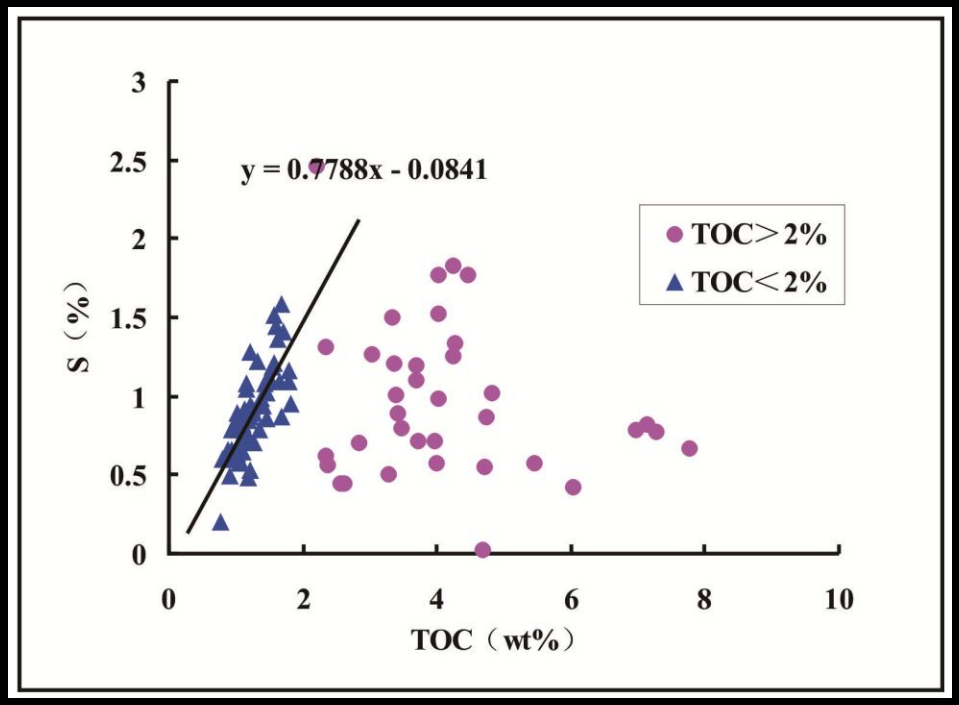
- TOC content is high in the Wufeng Formation and the bottom of the Longmaxi Formation (1.74%～4.54%).
- The thickness of high TOC content interval is ~25m.
- TOC content decreases (1.73% to 0.83%) in the upper part of the Longmaxi Formation and then keep of constant value about 1.26%.

The Vertical Change of Sulfur Content and Organic Matter Carbon Isotopes



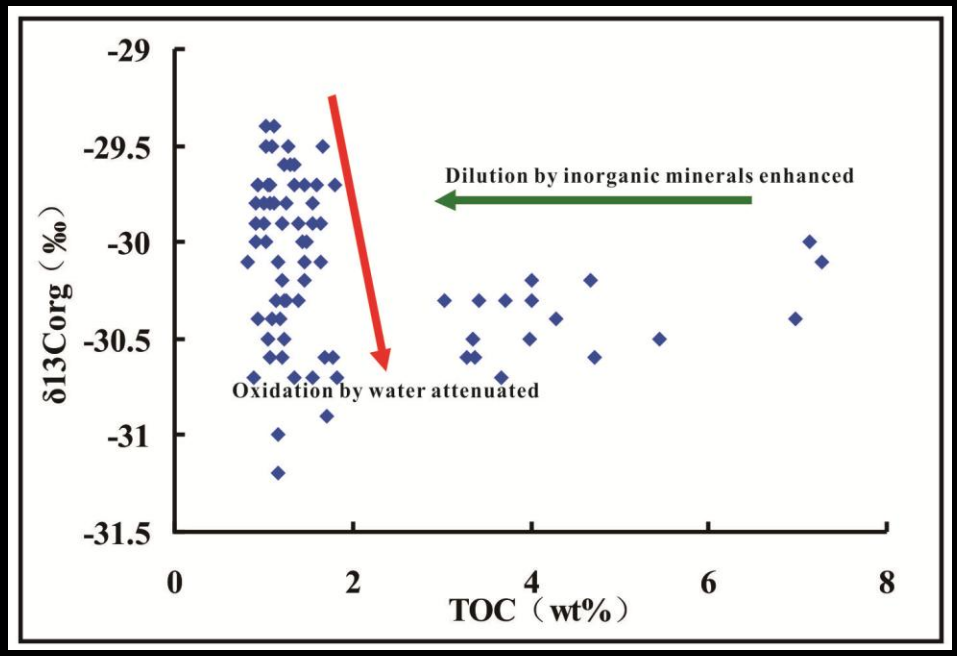
- The sulfur content is in the range 0.02% to 1.45% with an average of 0.9%.
- The $\delta^{13}C_{org}$ value of the Longmaxi shale is from -31.38‰ to -28.8‰ with an average of -30.3‰. It indicate that organic matter is type - Ⅰ and Ⅱ dominated.
- The vertical variation of the sulfur content and $\delta^{13}C_{org}$ value is similar to Shuanghe town profile in Changning county.

Relationship between Sulfur Content and TOC Content



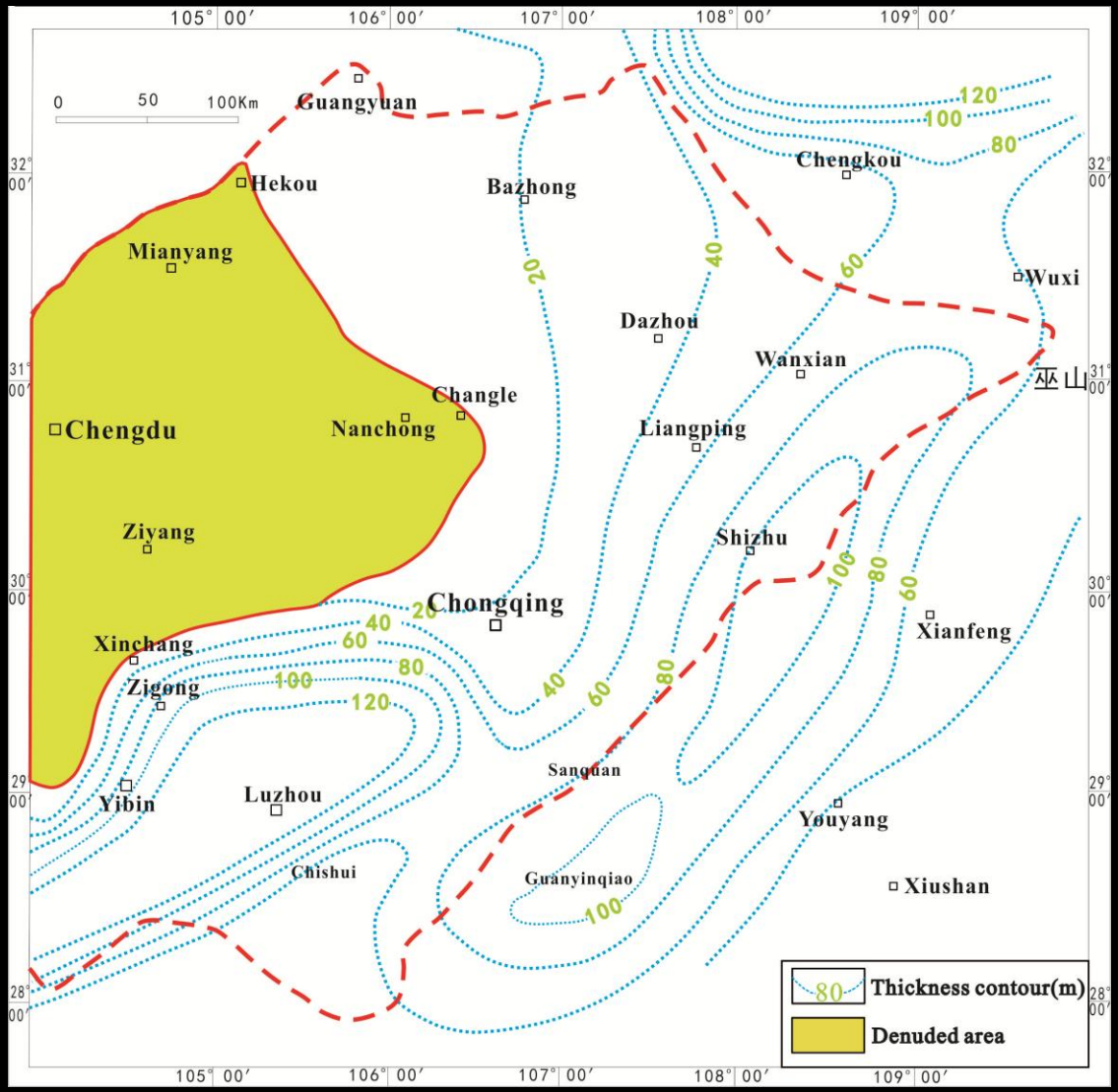
- A positive linear correlation with R^2 of 0.76 between TOC and sulfur content exists when TOC<2.
- It indicate a non-euxinic oceanic sedimentary environment.
- in contrast when TOC>2%, no correlation exists. It indicates an euxinic and anoxic oceanic sedimentary environment.

Relationship between δ13Corg Value and TOC Content



- The decrease in TOC contents is associated with the increase of $\delta^{13}C_{org}$ values while TOC<2%.
- It reflects that a strong oxidation in water leads to the poor organic matter preservation.
- The $\delta^{13}C_{org}$ values for TOC>2% samples is almost constant.
- It reflect that the dilution of inorganic minerals to organic matter content in the bottom of Longmaxi Fm.

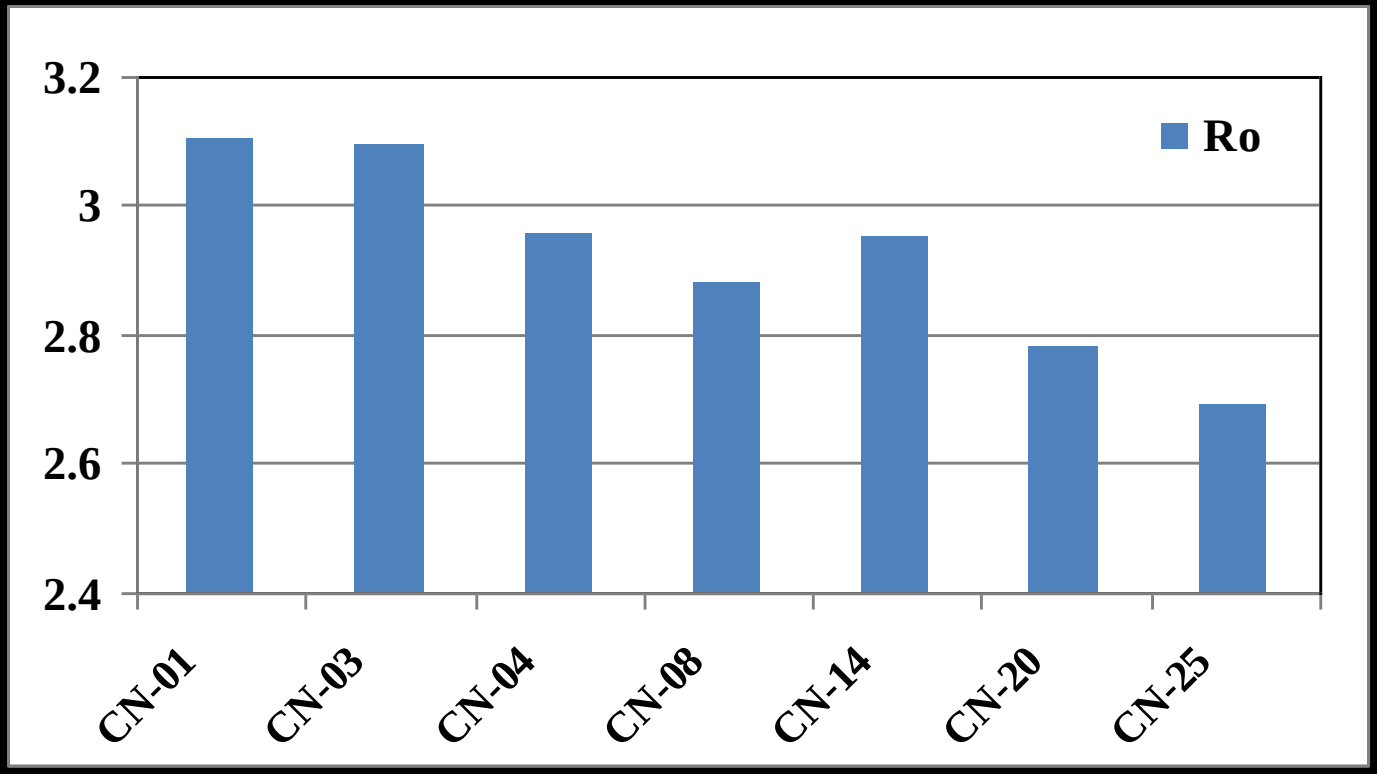
Thickness Contour of Longmxxi Fm. in Sichuan Basin



According to Wang Shejiao et al., 2009

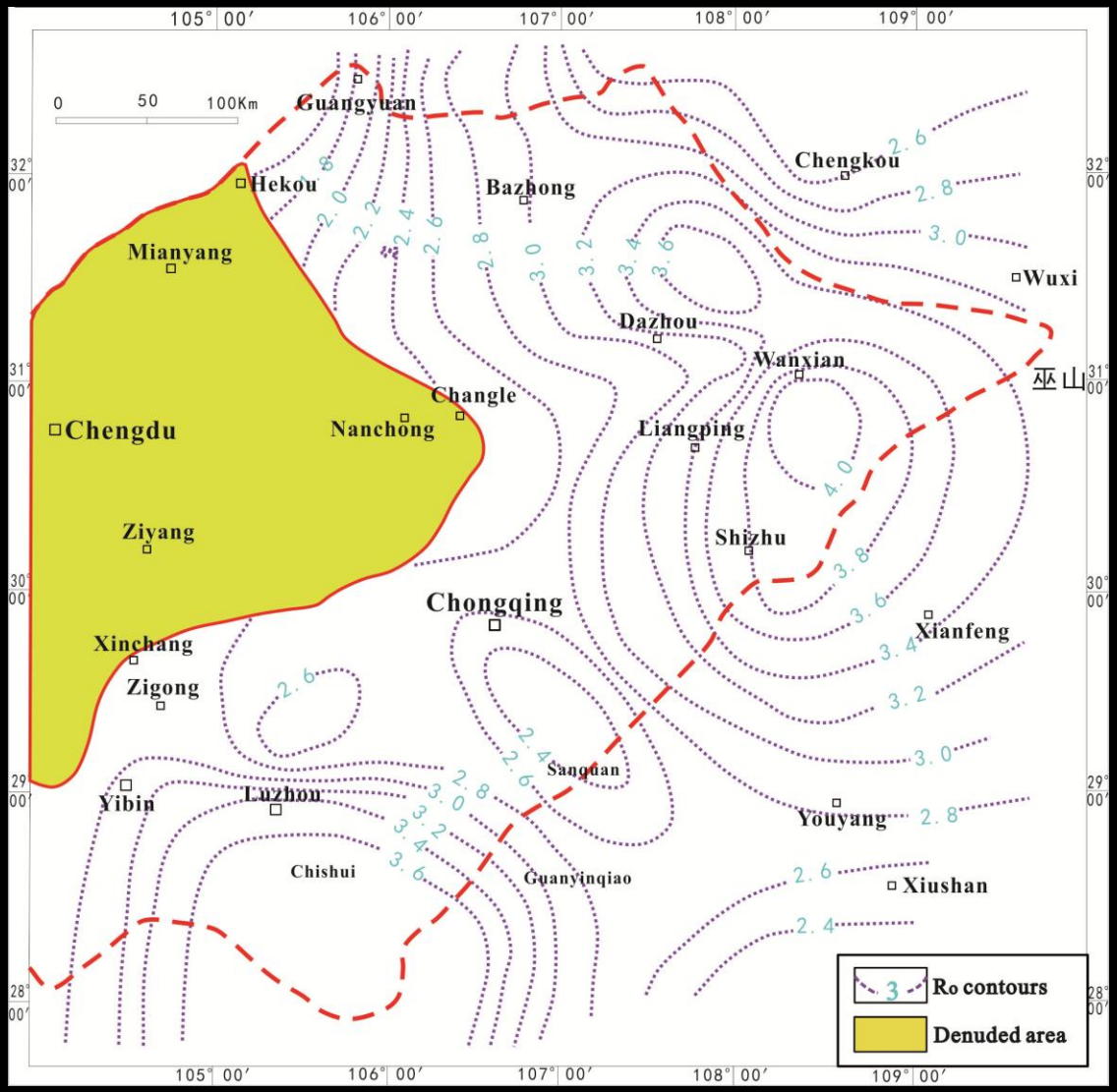
- No deposit in denuded area
- Two deposit centers
  - Shizhu—Lichuan area
  - Yibin—Luzhou area
- Maximum thickness reaches 120m

Thermal Maturity: Measured Ro



The values of Ro range from 2.69% to 3.10%, indicating high to over thermal maturation favorable to gas generation.

Ro Contour of Longmaxi Formation



- Two high maturity areas:
  - Shizhu—Wanxian area
  - Luzhou area
- Maximum Ro reaches 4.0%
- High TOC areas are associated with high thermal maturity.

According to Zhang Jingping et al., 2011

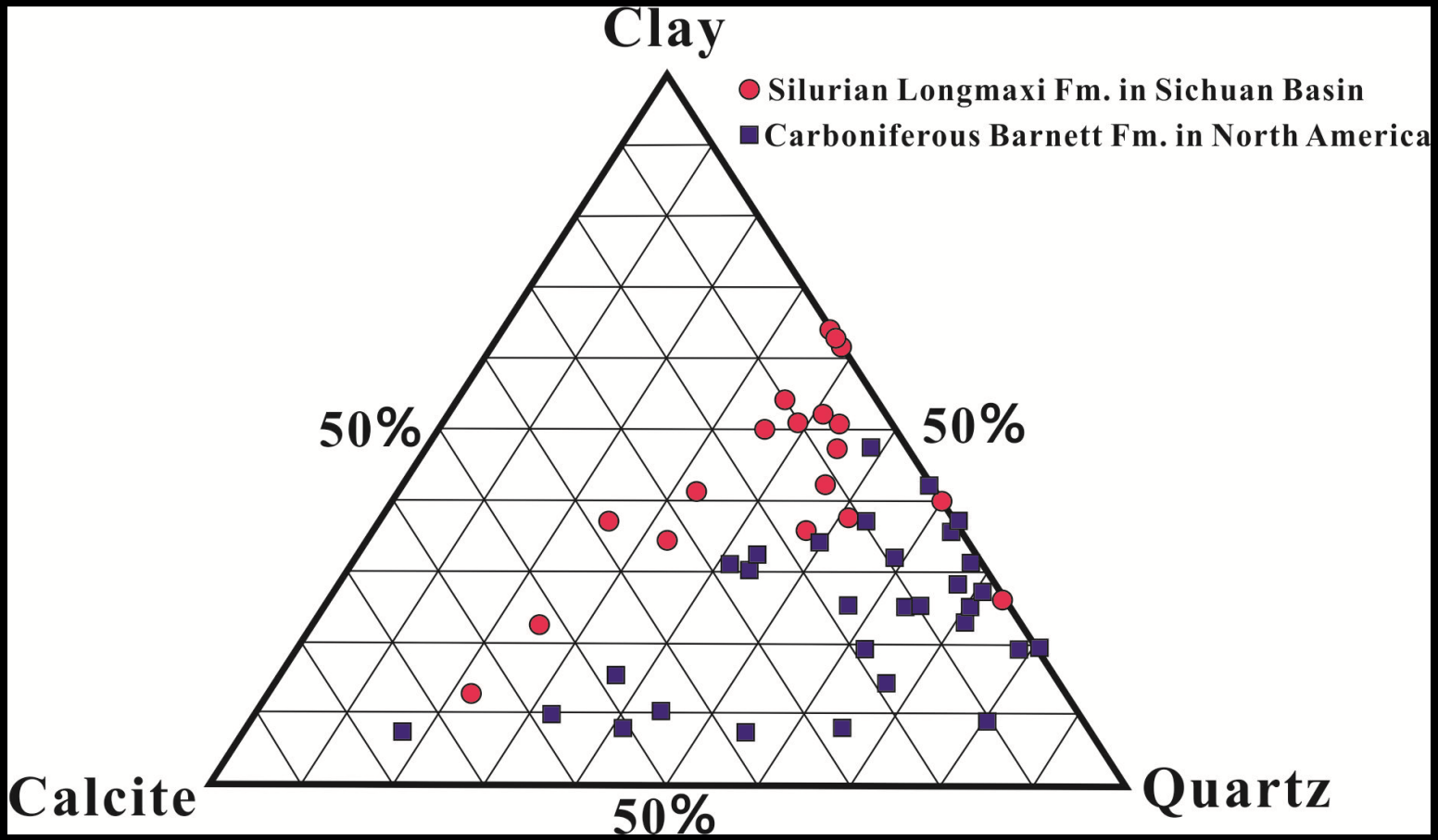
Mineral Compositions

Classification	Mineral	Content	Total
Brittle Minerals	Quartz	24.3%-43.5%	37.1%-71.2%
	K-Feldspar +Plagioclase	4.3%-10.8%	
	Calcite	8.5%-16.9%	
Clay Minerals	Illite	52.0%-80.0%	37.4%-48.3%
	Chlorite	10.0%-20.0%	
	Kaolinite	0-6.0%	

Acccording to Dong Dazhong et al., 2010

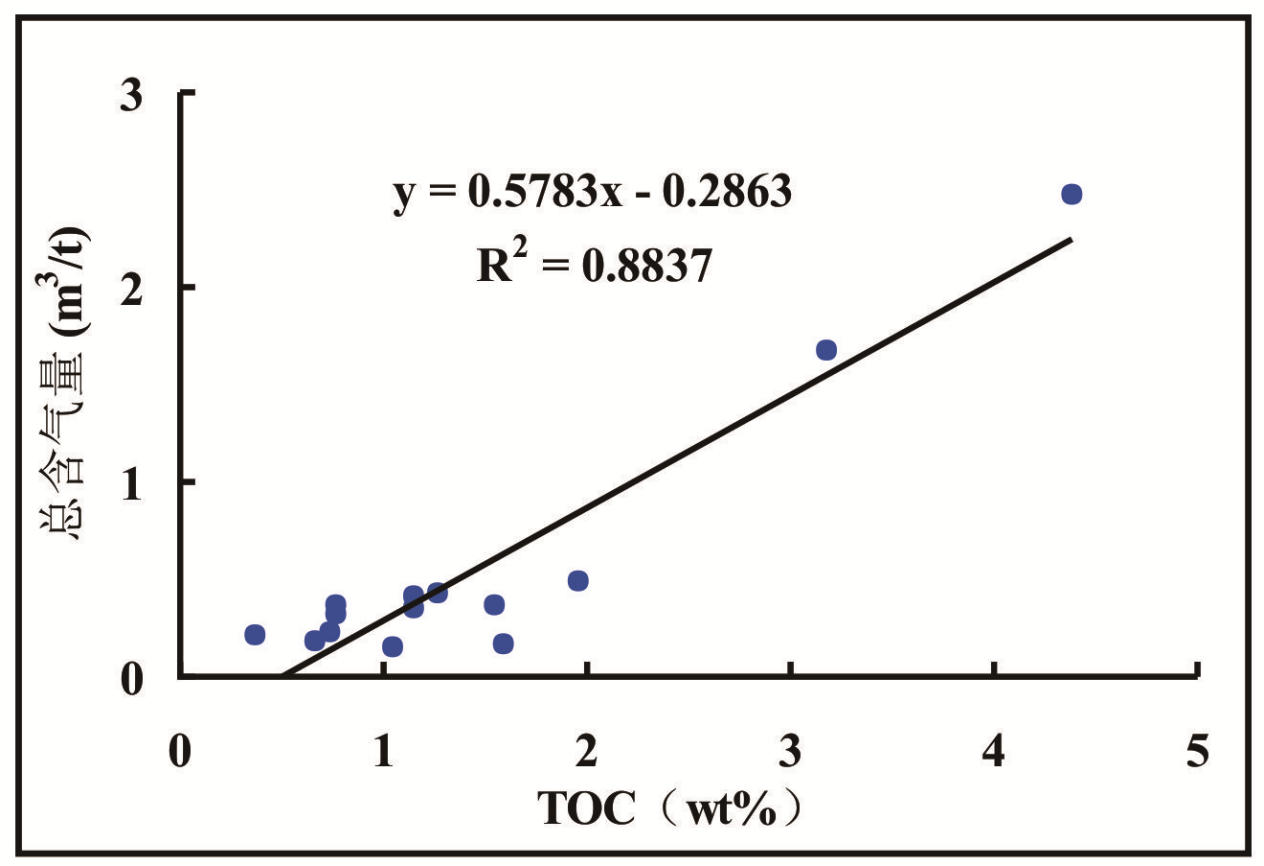
- The brittle minerals are abundant.
- Clay minerals are dominated by stable minerals, lack of swelling clay minerals like montmorillonite.

Major Mineral Composition Triplot



According to Jiang Yuqiang et al., 2010

Gas Content in Longmaxi Fm.
Relationship between Gas Content and TOC



- The gas content of Lngmaxi shale in Qianjiang district, Chongqing is in the range of 0.15 to 2.48m^3/t , with an averge of 0.56m^3/t.
- There is a positive linear correlation between TOC and gas content.

Fractures

Natural fractures, cracks and pores developed in the Longmaxi Fm. provide spaces for shale gas storing.

Joints and cracks distribute for network-shaped in 3D space.

Conclusion

- **The vertical variation in TOC content in Longmaxi Fm. reflects regional transgression, deepwater reducing environment and slow sedimentary rate.**
- **The lower part of Silurian marine mudstones in Sichuan basin is favorable target to shale gas exploration.**
- **TOC is the mean control for gas content for Longmaxi Fm.**
- **Large thickness of Source rocks areas are the most favorable area for shale gas development.**