Leached Secondary Porosity by Meteoric Water in the Upper Triassic Yanchang Formation of the Ordos Basin, China*

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Abstract

The Ordos Basin, covering an area of about 320,000 km^2, is located in northwest China. Being a dustpan-like basin with a gentle slope in the east and a steep slope in the west, it plunges from northwest to southeast (Ji et al., 2010). The major structural units of the Ordos Basin consist of the Yimeng Uplift in the north, Western Edge overthrust belt in the west, Tianhuan Depression, Yishan slope, Jinxi flexural belt in the east, and Weibei Uplift in the south (Figure 1).

The Ordos Basin belonged to a part of the North China Platform before the Early Triassic (Ji et al., 2010). In the Early and Middle Triassic, the Ordos Basin became part of the North China intracratonic depression, with sedimentary fill dominated by fluvial-lacustrine sandstone and mudstone (Zou et al., 2010). As a result of Indonesian Movement (regional collisional tectonism and related intra-plate deformation in the Late Triassic), the Ordos Basin evolved into a foreland basin, and the cessation of thrusting and subsequent erosion of the Liupan Mountains produced a regional unconformity in the Basin between the Triassic and Jurassic.

The Upper Triassic Yachang Formation is beneath the regional unconformity at the base of the Jurassic section, unconformably overlain by the Jurassic Yan'an/Fuxian Formation (Table 1), and the top of the Yanchang Formation was eroded in different degrees. Abundant oil resources are present in the Upper Triassic Yanchang Formation, which is part of a lake-delta sedimentary system with a thickness of about 500-1300 m (1640.5-4265.3 ft). The Yanchang Formation can be divided into 10 members, Chang 1 to Chang 10 from top down (Table 1). Chang 7 is the main hydrocarbon source rock, followed by Chang 4+5 and Chang 9. Chang 2, Chang 6 and Chang 8 are the most important reservoirs.

Results and Analysis

The Upper Triassic Yanchang Formation in the Ordos Basin is a typical sandstone reservoir with an ultra-low permeability. The results of 5008 samples of rock-mineral identification show that the reservoir lithology is mainly composed of lithic arkose, and feldspathic litharenite (Figure 2), averages of 34% quartz, 42.6% feldspar, and 21.4% lithoclasts. Feldspar is the most important component in the skeleton framework grains. The dissolution of feldspar and volcanic rock fragments is very common in the immature feldspar- and rock-fragment rich sandstones, which produce abundant secondary pores. The abundance of tabular or tabular-prismatic pore outlines and the residuals of precursor in pores are indicative of intragranular pores or moldic pores that formed by the partial or even complete dissolution of feldspar (Figure 3). Some of the pores are filled with kaolinite or carbonate cement (Figure 3). The results of thin section samples analysis show that the reservoir spaces mainly consist of primary and secondary pores.The secondary pores account for about half of the total pores, and are dominated by the feldspar-dissolved pores, with the avereage thin section porosity of about 1%, contributing to more than 50% of the total secondary porosity (Figure 4). Therefore, the dissolution of feldspar is significant in the diagenesis process.

Detailed study of the vertical variations of the whole secondary porosity and feldspar-dissolved pores, feldspar and kaolinite contents, reservoir properties, and the characteristics of typical well reflect that the generation of secondary porosity in the Upper Triassic Yanchang Formation is greatly influenced by meteoric water.

Vertical Variations in the Secondary Porosity of Yanchang Sandstone

The analysis of 5008 casting thin section samples of the Upper Triassic Yanchang Formation indicates that the upper part (mainly Chang 1 to Chang 3) has higher total porosity, which is attributed to the more secondary porosity mainly formed by the dissolution of feldspar (Figure 5), followed by the dissolution of debris. The inter-crystal porosity of kaolinite also increases from Chang 9 to Chang 1. Compared to Chang 6 close to the main source rock of Chang 7, the organic acid produced by kerogen maturation from Chang 7 is easier to migrate to the Chang 6, but harder to reach the upper members of Chang 1 and Chang 2. Therefore, it is supposed that the fluid of the dissolution of feldspar is not the organic acid from Chang 7 during the burial process. The dissolution in the Yanchang sandstones is probably related to the leaching by meteoric water during the subaerial exposure in the Indo-China period.

Vertical Changes in the Feldspar and Kaolinite Content of Yanchang Sandstone

The results of thin section identification of 5008 samples show that Kaolinite is abundant in the upper part of Yanchang sandstones but with a smaller content in the lower part. The kaolinite content shows a growing trend from Chang 9 to Chang 1, with the average content changing from less than 0.5% of the total rock volume of Chang 9 to more than 3% of Chang 1 (Figure 6a), while the changes of feldspar content indicate an inverse trend, that is, it gradually decreases from Chang 6 to Chang 1 (Figure 6b).

The XRD analysis of 978 samples reveals the same evolution as petrographic observation. The kaolinite increases with a closer distance to the unconformity, and the kaolinite content in total clay mineral of Chang 1 is up to about 30% (Figure 6c). On the contrary, the total feldspar content and K-feldspar content decreases gradually with a closer distance to the unconformity from Chang 9 to Chang 1 (Figure 6d). It is confirmed that the potassium depletion is caused by the dissolution of potassium feldspar, according to XRD analysis and petrographic observation, resulting in the precipitation of kaolinite occurring as pore fillings and creation of secondary porosity.

One of the important characteristics of the influence of meteoric water on sandstones in the near-surface is the dissolution of feldspar associated with the precipitation of kaolinite. The equation of the reaction of K-feldspar to produce kaolinite can be expressed as the following:

$$\underset{\text{K-Feldspar}}{2KAlSi_3O_8} + 16H_2O = \underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_4} + 2K^+ + 4SiO_2 + 2(OH)^- + 13\ H_2O$$

Vertical Changes in the Petrophysical Properties of Yanchang Sandstone

The statistical data of the rock's petrophysical properties (51,066 samples) show that the upper members of the Yanchang Sandstone, with a closer distance to the unconformity, has better reservoir properties, with an average porosity of about 15% and permeability of nearly 10 md, whereas the porosity of sandstones from deeper and farther from the unconformity ranges from 0.2% to 9.3%, and the permeability is less than 1 md, which leads to relatively poor reservoir quality in the lower members of Yanchang Formation. The measured data present a common characteristic that both porosity and permeability gradually reduce from the upper member close to the unconformity to the lower member far from the unconformity but with a closer distance to the main source rock of Chang 7.

Characteristics of Typical Well

The study on Well P, a typical well, also shows the characteristic that the upper members closer to the unconformity display lower feldspar content, correspondingly higher kaolinite content, higher thin section porosity, and more secondary porosity formed by the dissolution of feldspar (Figure 8). In addition, reservoir sandstones in the upper members of the Yanchang Formation are with higher measured porosity and permeability.

Conclusions

This article concludes that the leached secondary porosity by meteoric water is related to the unconformity of the Indo-China period in the Upper Triassic Yanchang Formation of the Ordos Basin, based on the following evidence: (1) the upper members of the Yanchang Formation, closer to the unconformity, have better reservoir properties (higher porosity and higher permeability) than those of the lower members; (2) the secondary porosity formed by the dissolution of feldspar increases with a closer distance to the unconformity; and (3) the upper members closer to the unconformity display lower feldspar content and correspondingly higher kaolinite content, and further petrographic study and XRD analysis confirm that the potassium depletion is caused by potassium feldspar dissolution, resulting in the precipitation of kaolinite and creation of secondary porosity.

The leaching by meteoric water during Indosinian exposure interval leads to the generation of secondary porosity in the Upper Triassic Yanchang Formation. In particular, meteoric water influences the Upper members of Yanchang Formation. Therefore, the prediction model of reservoir quality should consider the generation mechanism of secondary porosity, and many variables such as paleoweather, paleogeomorphology, surface runoff, and the relationship between weathering rate and the rate of tectonic uplift, as very important in the prediction of reservoir quality.

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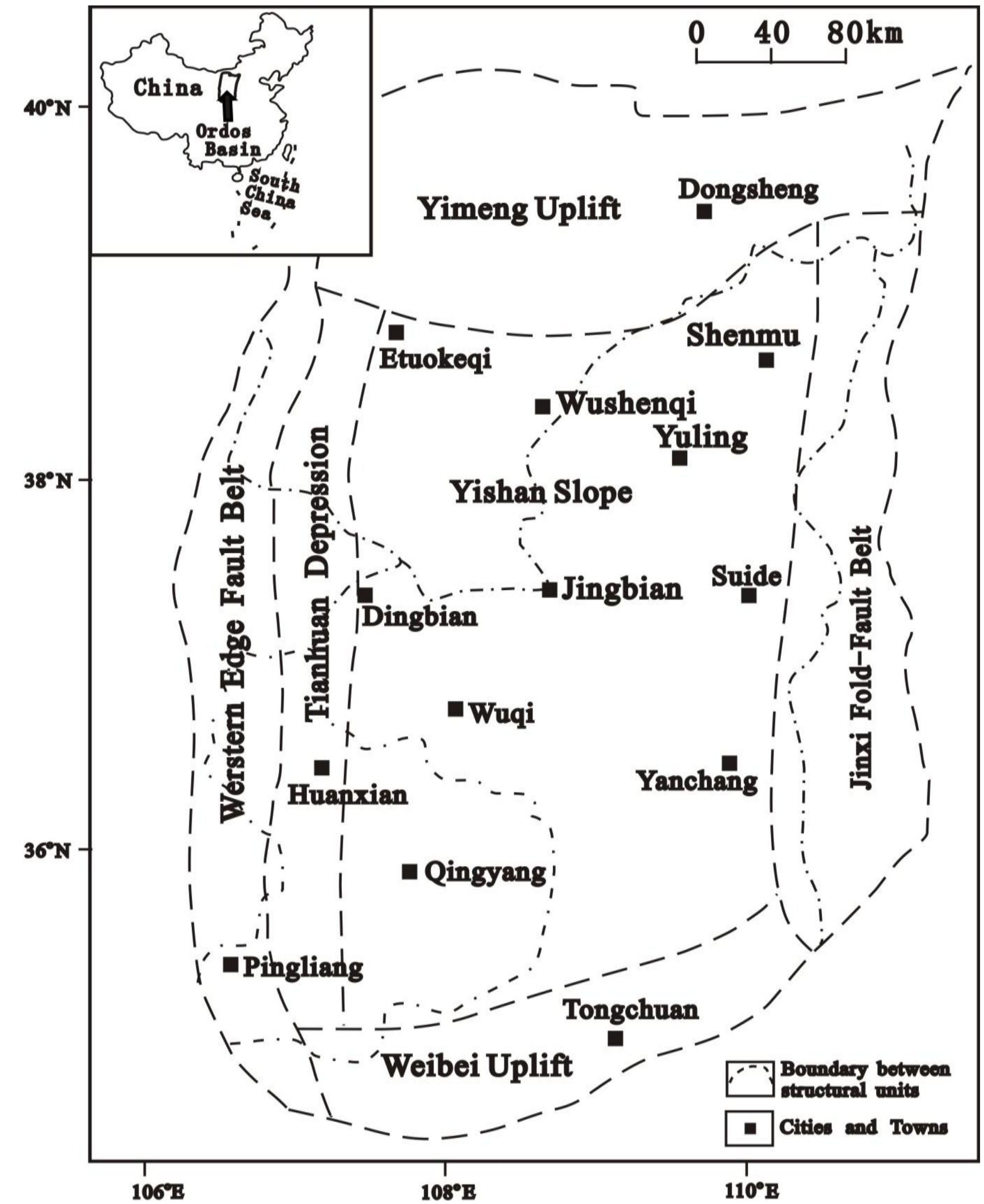

Figure1. Schematic map showing the Ordos Basin (from Editorial Committee of Petroleum Geology of Changqing Oilfield, 1992).

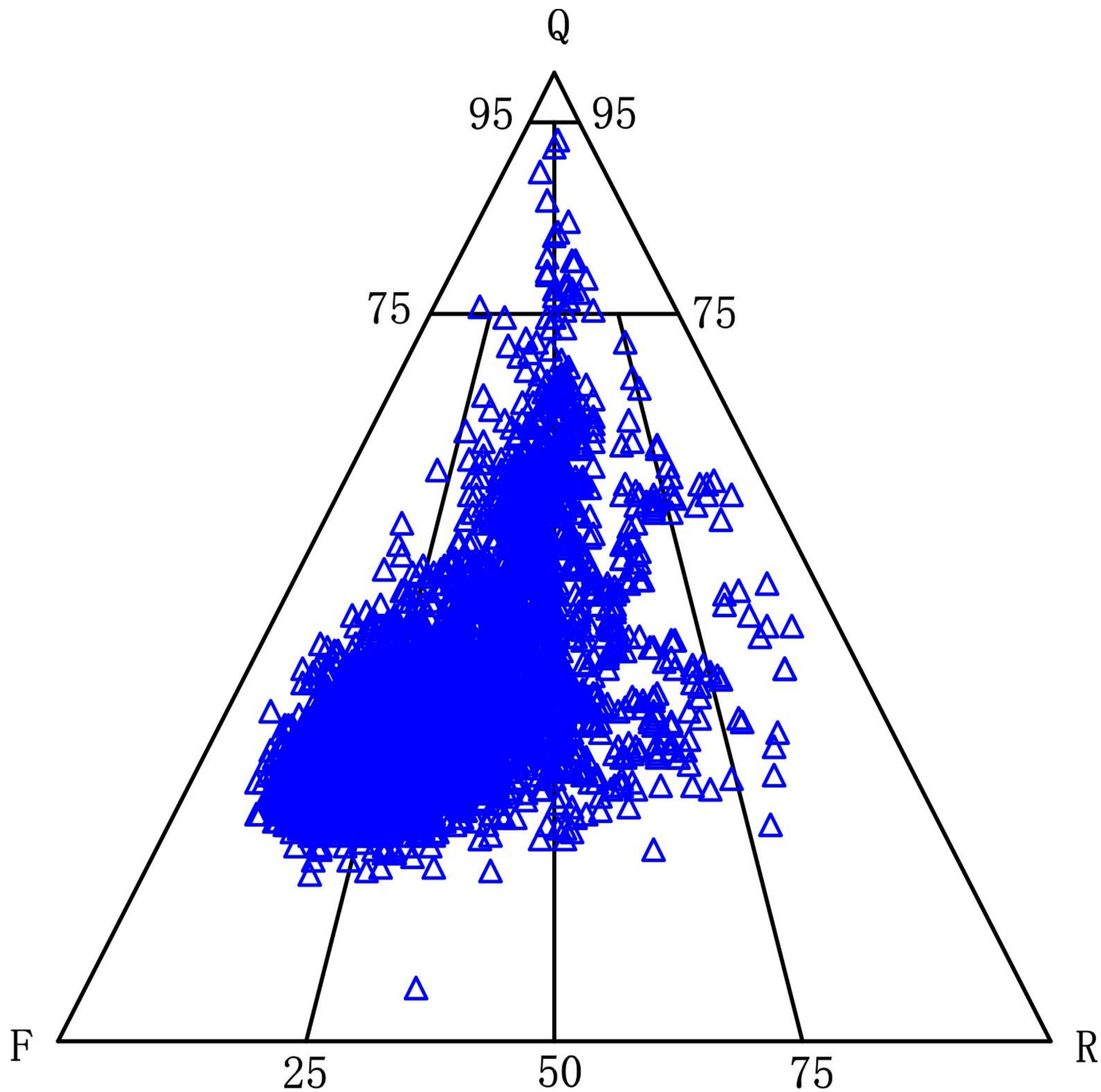

Figure 2. Classification triangle of Yanchang sandstones.

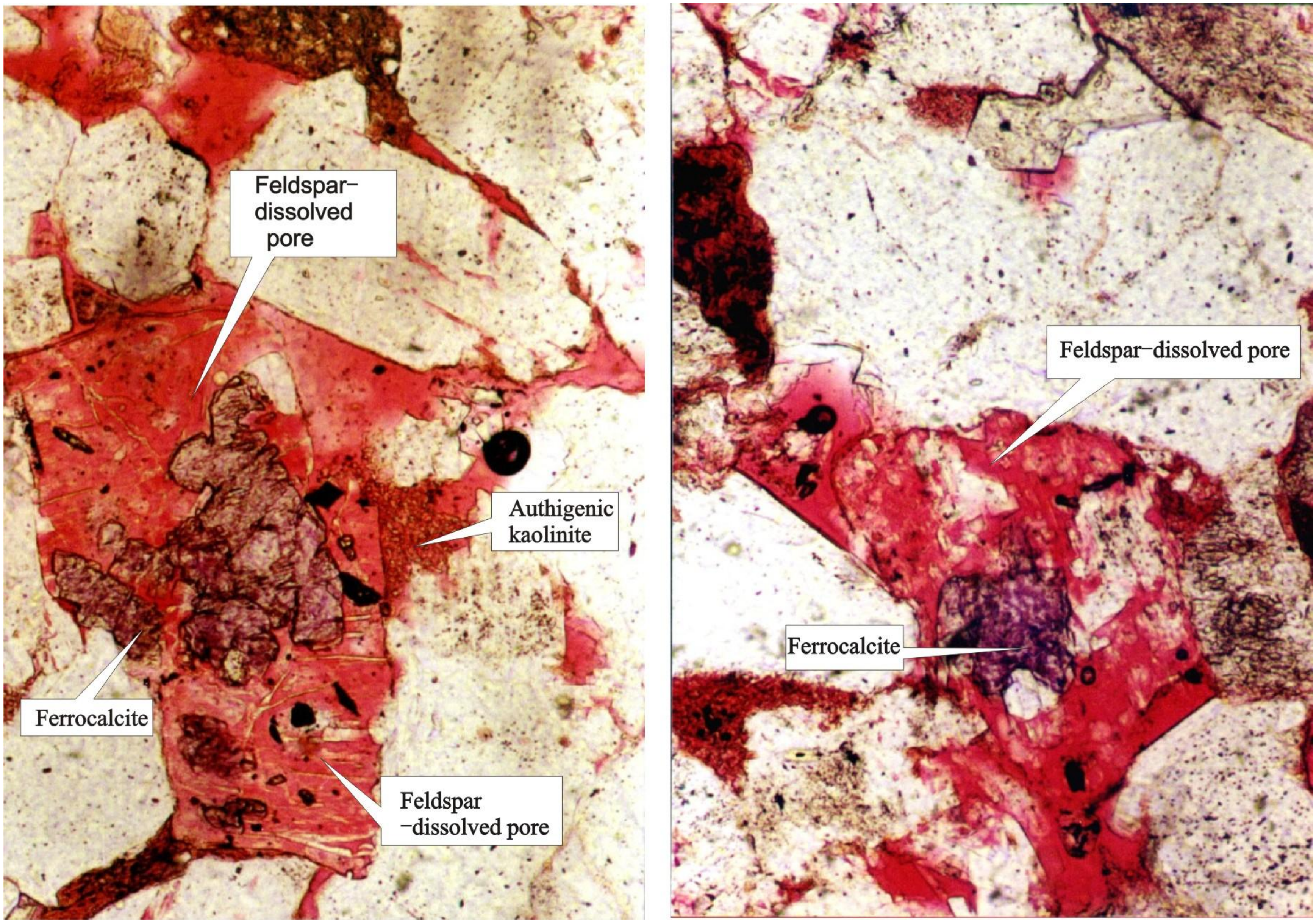

Figure 3. Thin section microphotographs showing the dissolution of feldspar, the generation of secondary porosity and the precipatation of kaolinite, stained with a combination of Alizarin Red S and potassium ferricyanide, plane-polarized light, diagonal of 1.75.

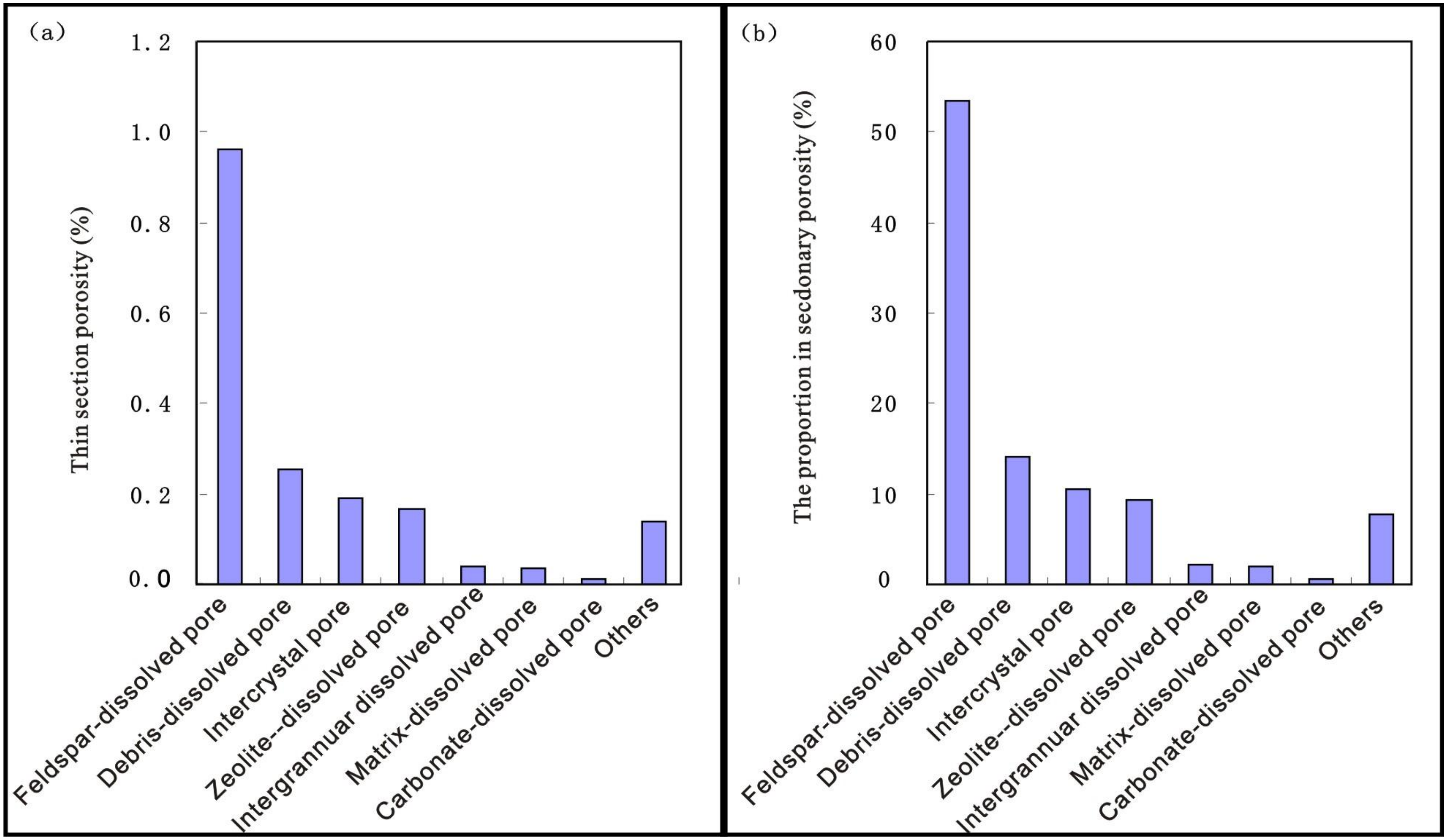

Figure 4. Thin section porosity of different types of pores (a), and the respective proportion in the secondary porosity (b).

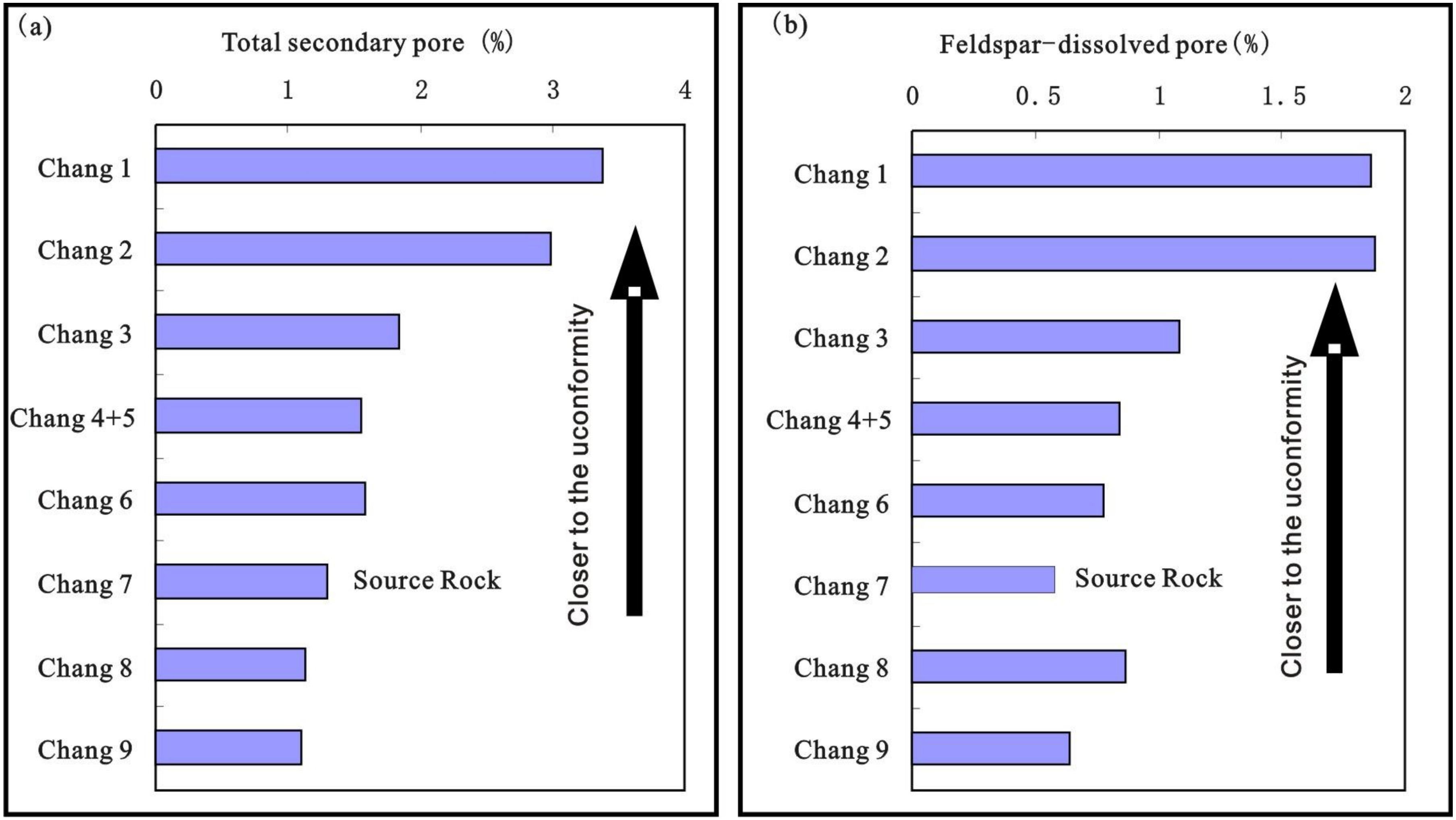

Figure 5. Vertical variations in the total secondary porosity (a), and feldspar-dissolved pores of Yanchang Sandstone (b).

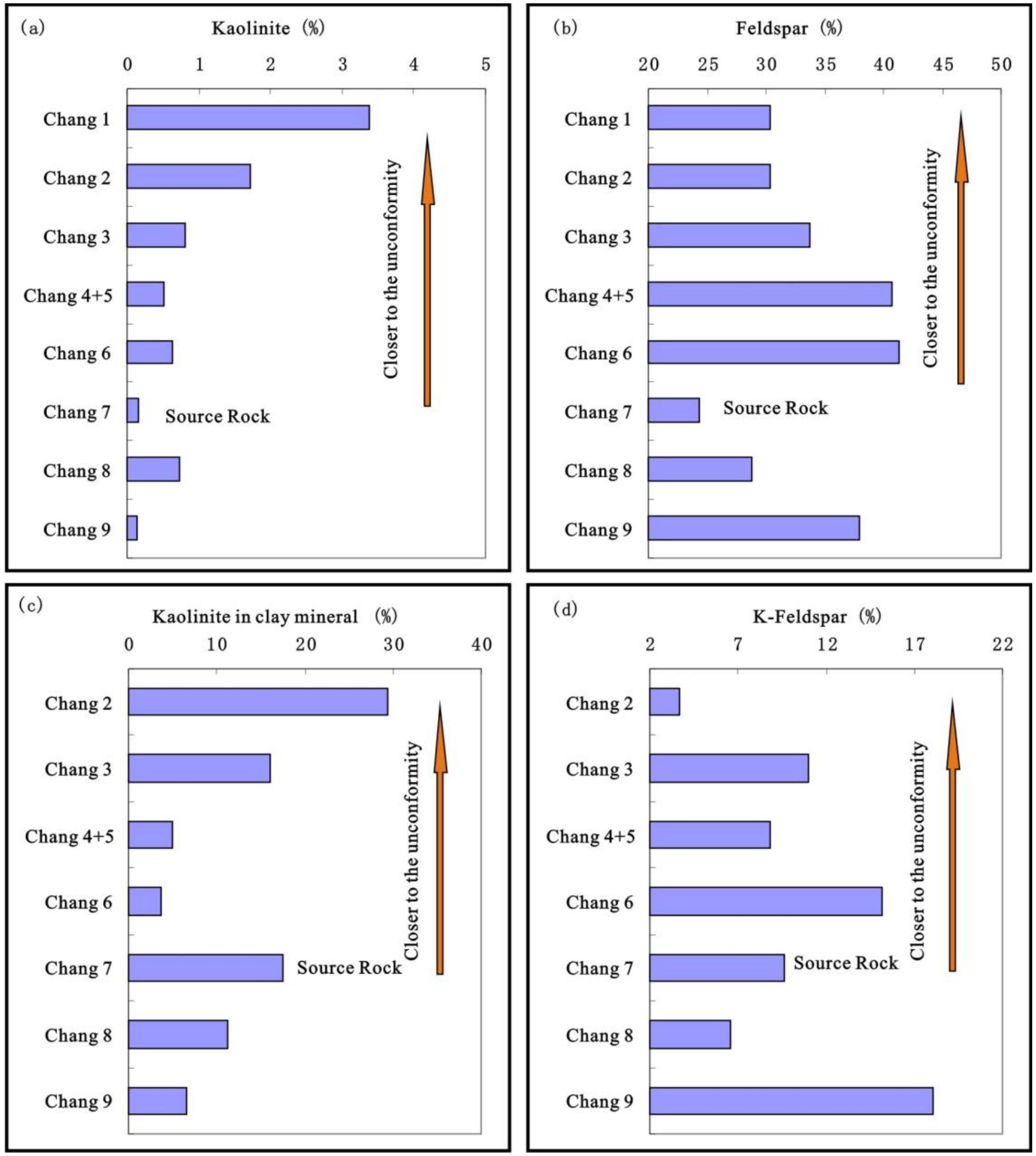

Figure 6. Vertical variations in the kaolinite and feldspar contents by thin section identification (a-b), and the XRD data showing the changes of kaolinite content in clay mineral and K-Feldspar of Yanchang Sandstone (c-d).

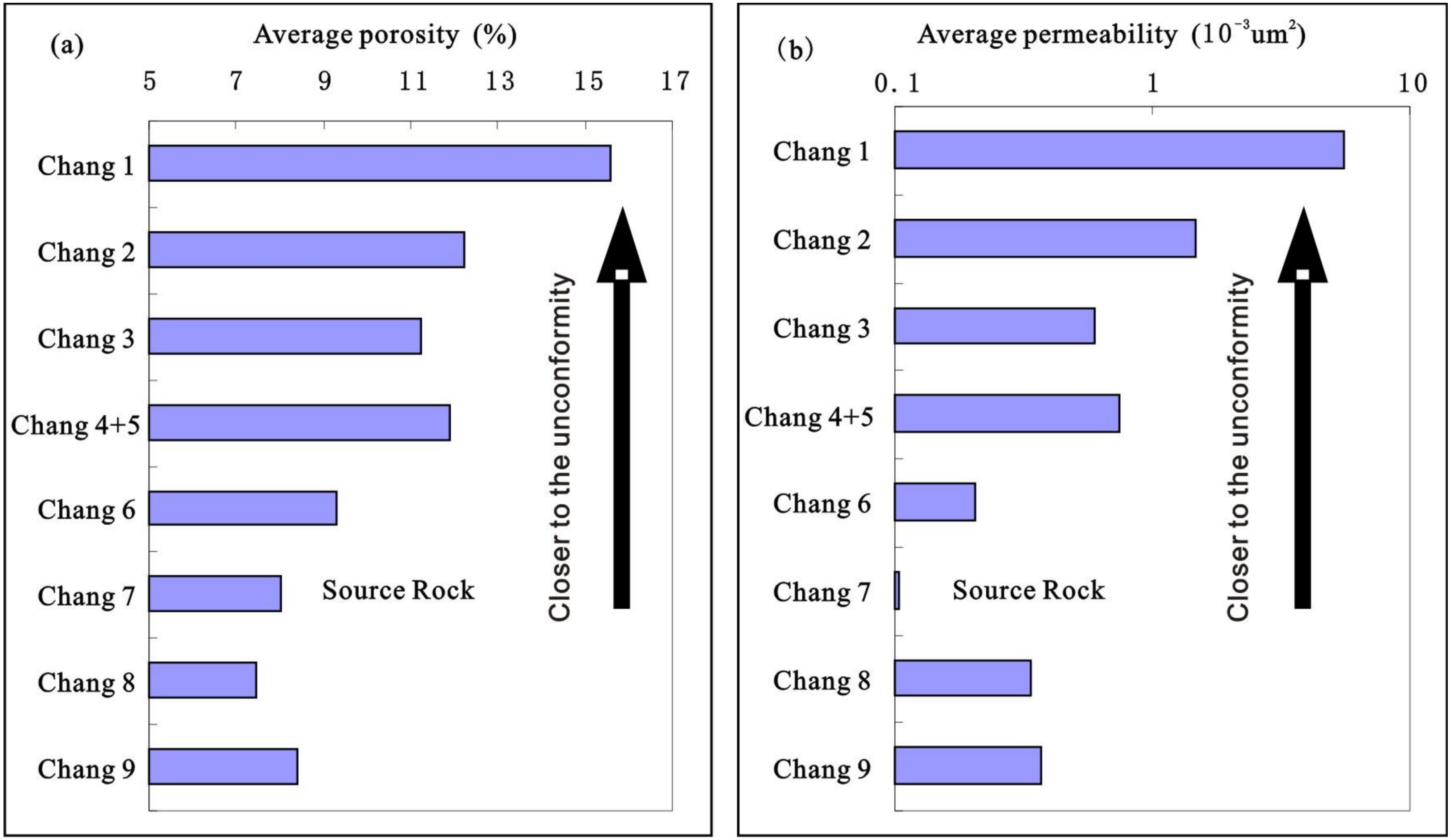

Figure 7. Vertical evolution of porosity and permeability of Yanchang Sandstone (51,066 samples).

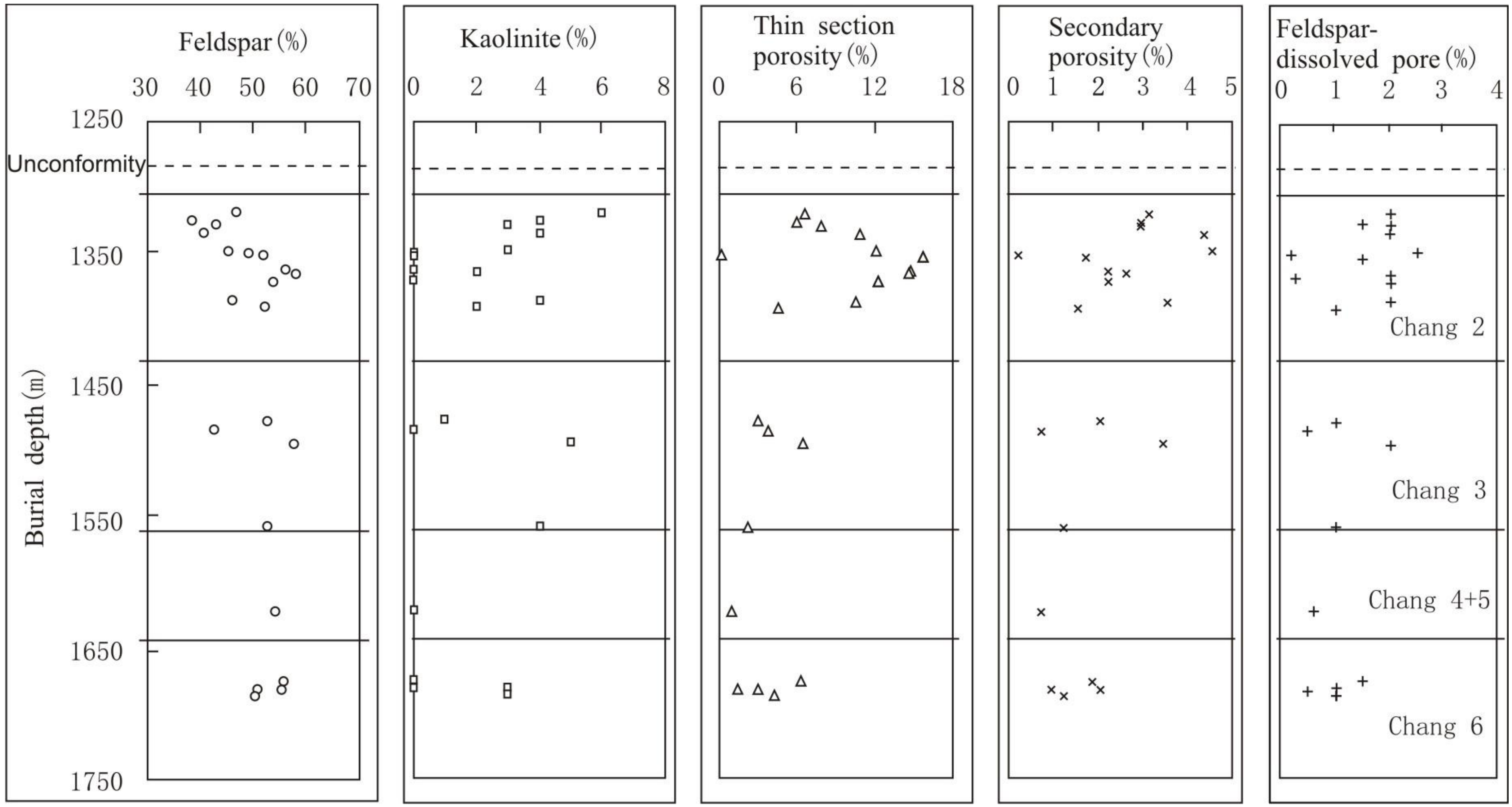

Figure 8. Vertical evolution of contents of authigenic kaolinite and feldspar, thin section porosity and secondary porosity formed by the dissolution of feldspar, Yanchang Sandstone in Well P, Ordos Basin.

Series	Formation	Member	Thickness(m)	Lithology
Jurassic	Yan'an / Fuxian	Formation		
Triassic	Yanchang Formation	Chang 1	0-240	Dark mudstone, muddy siltstone, fine-medium-grained sandstone, interbedded with carbonaceous mudstone and coal seams. Disconformities are distributed broadly due to denudation.
		Chang 2	0-150	Grayish green massive fine-grained sandstone interbedded with dark mudstone. Disconformities are distributed locally due to denudation.
		Chang 3	120-150	Gray, grayish brown fine-grained sandstone interbedded with dark mudstone.
		Chang 4+5	80-110	Light gray silt-fine-grained sandstone interbedded with dark mudstone.
		Chang 6	100-130	Brownish gray, massive fine-grained sandstone, silt-fine-grained sandstone, muddy siltstone, light-grayish black mudstone, interbedded with thin tuff.
		Chang 7	80-100	Dark mudstone, carbonaceous mudstone, oil shale interbeddedwith thin silt-fine-grained sandstone.
		Chang 8	70-85	Dark mudstone, sandy mudstone interbedded with gray silt-fine-grained sandstone.
		Chang 9	90-120	Dark mudstone, shale interbedded with gray silt-fine-grained sandstone.
		Chang 10	50-300	Gray thick-massive medium-fine-grained sandstone with the bottom coarse-grained sandstone.
	Zhifang	Formation		Grayish purple mudstone, sandy mudstone interbedd with medium-fine- grained sandstone.

Table 1. Subdivisions of the Upper Triassic Yanchang Formation (from Editorial Committee of Petroleum Geology of Changqing Oilfield, 1992; Zhou et al., 2010).