Palaeoenvironmental Changes of the Ancient Nihewan Lake Area—Sr Isotope Evidence from Xiaodukou Foraminifera*

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Abstract: By using the improved trace (50 μg) Sr isotope analytical method the $^{87}Sr/^{86}Sr$ ratios of Xiaodukou foraminifera fossils were measured, giving a range of 0.71105 – 0.71274, apparently higher than the value of contemporaneous seawater (0.709087 – 0.709147) and also slightly higher than the average value of modern Yellow River (0.7111), demonstrating that the contemporaneous environment where Xiaodukou foraminifera inhabited was an inland lake. Detailed analyses of ΔSr values showed that there occurred an event responsible for environmental changes in the ancient Nihewan Lake area during the time (about 1.0 Ma ago) when Xiaodukou foraminifera appeared. Because of strong evaporation the salinity of the lake would increase and a regional salt-water or brackish-water lacustrine environment would be produced, thus providing a suitable and inhabitable environment for foraminiferae. It is concluded that Xiaodukou foraminiferal fossil assemblages belong to non-marine foraminiferal species.

Key words: **foraminiferal fossil; Sr isotope; continental facies; Nihewan Group**

Introduction

Foraminifera is a typical marine organic species. Its facies-indicating function is widely applied in the study of transgression in the Quaternary or earlier geological periods and fruitful results have been achieved. However, in the last decades, with the development of oil and natural gas exploration and investigation of Mesozoic and Cenozoic continental strata, foraminiferal fossil assemblages were found in many typical Quaternary and Early Tertiary continental strata in the inland basins of eastern China, such as the Nihewan Basin, Hebei Province, the Yuncheng Basin, Shanxi Province, the Qianjiang Basin, Hubei Province, the Jiyang Depression, Shandong Province, as well as in Cretaceous strata in the Sichuan Basin. It is interesting to note that all Early Tertiary foraminiferal fossil assemblages found in the inland areas of eastern China are preserved in oil-bearing strata, so the fact about the relationship between the inhabitant environment for foraminiferal fossil assemblages and the formation of oils and natural gases has attracted much attention of the geologic circles.

To sum up, there exists two kinds of viewpoints in academic circles:

1. The inhabitant environment for foraminiferal fossil assemblages has something to do with the sea. Advocators of this viewpoint suggested that the strata containing foraminiferal fossil assemblages in the inland areas of eastern China were formed as a result of transgression (Wang Nanwen, 1987), or that after the basin containing foraminiferal fossil assemblages was formed, it did not close totally and hence there existed "channelways" to connect with the sea through which seawater could enter the basin irregularly (Wang Qian, 1986), or that the strata represented the

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weakly marine transitional deposits (Wang Pinxian and Lin Jingxing, 1974). In one word, those researchers stressed that the occurrence of foraminiferae is indicative of a marine or transitional environment which bears some relationship with the sea either spatially or temporally. According to this viewpoint, the inland areas of eastern China were affected by transgression in the early period of Tertiary, leading to the death of freshwater organisms in large amounts and alternately making eucryhaline organisms thriving. The thriving of marine organisms, especially planktons, of which the high abundance and good species were favorable to oil generation, created the material basis for the formation of oil; furthermore, some researchers suggested that the oil-generating environment in eastern China could be compared with the Tertiary brackish-water environment prevailing in those famous oil fields in Venezuela, Middle East, Middle Asia, and so on (Qiu Suanyu and Hu Bingli, 1994); in addition, foraminiferal fossil assemblages found in the area of North China should represent a hundred-meter subsiding of the area at that time.

2. Opponents suggested that the inhabitant environment for foraminiferal fossil assemblages has nothing to do with the sea. In the inland areas of eastern China, those basins containing foraminiferal fossils were totally separated from the sea at the beginning of their formation. If the chemical condition of a lake evolved to that of the sea, the appearance and development of foraminiferae would be possible (Wang Pinxian and Ming Qiubao, 1985; Song Zhengcheng et al., 1992). Examples cited by the opponents are sporadic reports about modern non-marine foraminiferal species in modern salty lakes around the world. Unfortunately, those modern species have not been found until now in China. If it is true, what would the inhabitant environment for those non-marine foraminiferal fossil assemblages represent and what relationships would exist between foraminifera and oil generating? It is the findings of those special foraminiferal fossil assemblages that leave a difficult problem to be answered in the study of Cenozoic geology in China.

Achievements in recent years show that it is difficult to distinguish foraminiferal assemblages in modern salty lakes from those in weakly marine environments such as supratidal zones and lagoons (Wu Nanqing, 1993; Wang Pinxian, 1992). Wang Pinxian (1992) pointed out that because of significant differences in chemical and isotopic compositions between lacustrine water and seawater, shell chemistry may be the way out to solve this problem. In the last decade $^{87}Sr/^{86}Sr$ ratios have been measured precisely in different geological periods since the Phanerozoic era, providing the basis for distinguishing marine from non-marine strata. In this paper, by using the improved trace (50 μg) Sr isotope analytical method, the author discusses the depositional environment of the foraminiferal fossil assemblage-containing strata measuring 12 m in thickness from the Xiaodukou section in the Nihewan Basin.

Geological Background of the Working Section

Xiaodukou, one of the depositional centers for the ancient Nihewan Lake, is located at Yangyuan County, Hebei Province, 300 km far from the modern coastal line and 500 m at sea level (Fig. 1). Lacustrine and river sediments were intercrossed spatially and temporally from Neogene to Middle Pleistocene in the Xiaodukou section, where mammal animals, foraminiferal fossils and plentiful ostracod and spore fossils were found. Because foraminiferal fossils were preserved in the 28th bed and the upper part of the 27th bed (Chen Maonan et al., 1988), in this work only the 27th, 28th and 29th beds were sampled consecutively in the interval of 25 cm. The 27th bed consists of yellowish-brown sandy silts interbedded with thin-bedded clay; interbedded sand and gravel, coarse sand and thin-bedded clay exist at the bottom of the 28th bed, and in descending order of grain size of sands and silts the yellowish-brown sands slowly become fine upwards; the 29th bed is composed of pale brown muddy silt and silt. In the total 12.4 m-thick strata including the upper 1.6-m part of the 27th bed and 28th bed, one kind of foraminiferal species "*Nonion shansiensis*" with a great variety of unusually shaped shells among individuals was found, approximately 0.20 mm and 0.10 mm in shell diameter and height, respectively. In addition to eucryhaline *S. impressa*, other ten kinds of freshwater ostracod species are recognized in the same strata dominated by *Limnocythera*, *Ilyocypris* and *Cytherissa*. The distribution density of lacustrine ostracods in the strata is proportional to that of foraminiferae and the amount of those two kinds of microfossils in the sand bed is higher than that in the clay bed on average. Because of the requirement of analytical amount, the sample containing 300 individual foraminiferae per kilogram was chosen for Sr isotope measurement (Fig. 1).

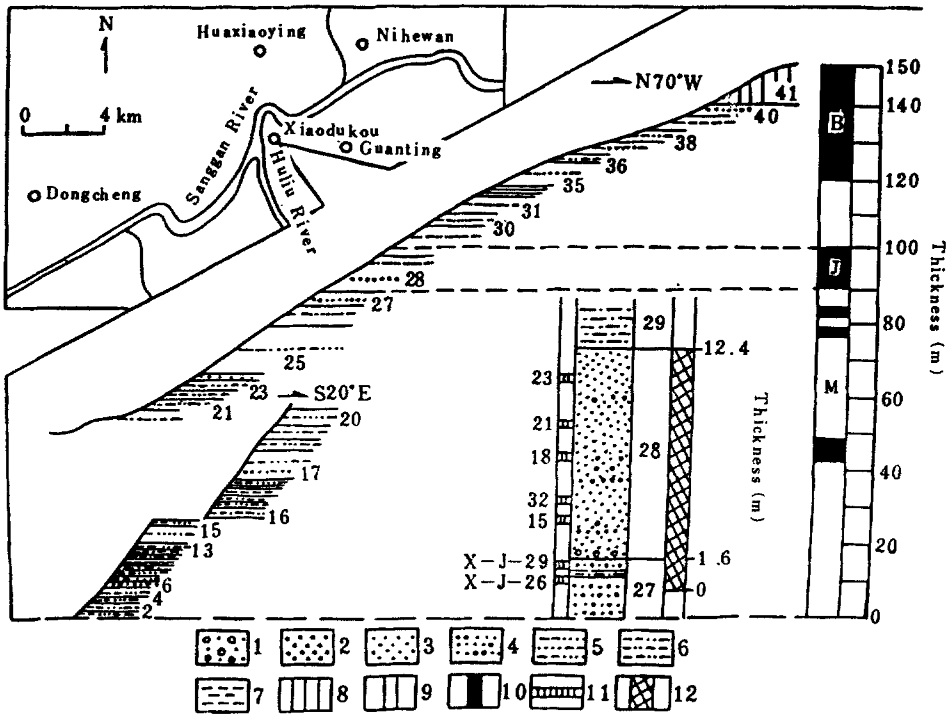

Fig. 1. Stratigraphy and sample localities of the Xiaodukou section. 1. Sand and gravel; 2. coarse sand; 3. sand; 4. sandy silt; 5. muddy silt; 6. silty clay; 7. clay; 8. loess; 9. reversal of the magnetic field; 10. positive magnetic pole; 11. sample point; 12. strata containing foraminiferal fossil assemblages. Data on the lithology, strata and palaeomagnetism are cited from Chen Maonan et al., 1988.

Palaeomagnetic measurements on the Xiaodukou section showed that the Jaramillo palaeomagnetic event (0.90 – 0.97 Ma) began at the top of the 27th bed and endded at the bottom of the 29th bed (Chen Maonan et al., 1988), the depositional time of the 28th bed was from 970 to 908.3 thousand years estimated on the average sedimentation rate: 15.71 cm/ka (Chen Maonan et al., 1988). On the basis of the average sedimentation rate of 7.99 cm/ka at the whole Xiaodukou section (Chen Maonan et al., 1988), the depositional time of the upper part of the 1.6 m-thick foraminiferal fossil assemblage-containing 27th bed was estimated at $990 \times 10^3 - 970 \times 10^3$ years. So, the living time of foraminiferal fossil assemblages in the Xiaodukou section was approximately from 0.99 Ma to 0.9087 Ma.

Modern species of "*Nonion shansiensis*" were sampled from a man-made canal at Luchaogang, Nanhui County, Southeast Shanghai. The canal is full of water and the salinity is low all the year round, varying from 1.37‰ to 2.36‰. The salinity in the canal is within the range of 1.85‰ – 1.87‰ at the time of sampling.

Material and Method

500 g of the samples were soaked in distilled water for 24 h and scattered spontaneously. By using the standard sieve to grade in distilled water, grains, larger than 0.09 mm in diameter, were selected to evaporate till dryness at temperature 80 – 90℃ and weighed. Then, the dry samples were floated in CCl_4 and foraminiferal fossil assemblages were concentrated. 40 – 60 individual foraminiferae, each of which had a clean external surface and measured ± 0.20 mm and ± 0.10 mm in shell diameter and height respectively and ± 1 μg in weight as determined on an electrostatic balance, were hand-picked out carefully under a binoscope as an analytical test at one time. Before measurement, all foraminiferal fossil samples were immersed in H_2O_2 for 1 h, and then repeatedly washed (three times) by using deionized water and ethanol. The chemical techniques available for separating Sr isotopes in China require more samples, ± 10 mg, but the amount of microfossil usually encountered in many research works cannot satisfy this requirement. The separating technique specially designed by us recently only requires ± 50 μg sample. Test samples were dissolved in 5% HAc. The solution was centrifuged and evaporated to dryness, followed by changing acetate into chloride in 1N HCl and being directly loaded onto the Dowex-50 W × 8 resin column (200 – 400 mesh). By using 1N HCl as washing liquid, the first 30-ml liquid was discarded and the following 20-ml Sr-rich liquid was collected. The Sr-rich liquid was purified again by passing it through the Dowex-50 W × 8 resin column (100 – 200 mesh). The total Sr blank for this procedure was 5×10^{-9} g and $^{87}Sr/^{86}Sr$ ratio measured for standard NBS 987 was 0.710229, 2σ mean for 0.003%. All $^{87}Sr/^{86}Sr$ ratios were measured on a VG-354 mass spectrometer at the Tianjing Institute of Geology, Ministry of Metallurgy, China.

Analytical Results and Discussion

Sr deposited together with calcite minerals does not fractionate in any kind of water, so, if they do not undergo chemical alteration after deposition, Sr-bearing calcite minerals will record $^{87}Sr/^{86}Sr$ ratios in contemporaraneous water where they were deposited. Two criteria were used to evaluate diagenetic alteration. Firstly, foraminifera with clean external surface was picked out under the binoscope; secondly, samples were thought to be recrystallized if examination by scanning electric microscope (SEM) revealed dissolution or secondary enlargement both in interior chamber surface and in chamber wall. Systematic SEM examination showed that the test samples had clean surface and apparent pore structure in the interior chamber surface and good columnar structure in the chamber wall (Photo 1d, e and f). Compared with SEM photo (Photo 1a, b and c) of modern species, it is clear that Xiaodukou foraminera has basically preserved the original structure, suggesting that it did not undergo apparent chemical alteration once it was buried. The contribution of *in-situ* decay of ^{87}Rb to the concentration of ^{87}Sr could be neglected due to its low concentration in the calcite minerals (Neat et al., 1979; Martin and Macdougall, 1991). So, $^{87}Sr/^{86}Sr$ ratios measured for Xiaodukou foraminiferal skeleton minerals represent $^{87}Sr/^{86}Sr$ ratios of contemporaraneous water where it was deposited.

Table 1. $^{87}Sr/^{86}Sr$ ratios in Xiaodukou foraminiferal fossils

Sample No.	Bed No.	$^{87}Sr/^{86}Sr$	ΔSr**
23		0.71143 ± 8*	32.6
21		0.71105 ± 18	27.3
18	28	0.71165 ± 12	35.7
32		0.71146 ± 12	33
15		0.71274 ± 16	51.1
X-J-29	27	0.71274 ± 5	51.1
X-J-26		0.71146 ± 12	33
Luchaogang		0.71083 ± 18	23

* Average standard error; ** $\Delta Sr = [\frac{(^{87}Sr/^{86}Sr)_{sample,\,t}}{(^{87}Sr/^{86}Sr)_{seawater,\,t}} - 1] \times 10^4$; when $t = 0.95$ Ma, $(^{87}Sr/^{86}Sr)_{seawater} = 0.709117$ (Hodell et al., 1990); when $t = 0$, $(^{87}Sr/^{86}Sr)_{seawater} = 0.7092$ (Hess et al., 1986).

The measured $^{87}Sr/^{86}Sr$ ratio and ΔSr for Luchaogang foraminifera are 0.71083 and 23, respectively (Table 1), slightly lower than the average value of modern Yangtze River: 0.7109 (Plamer and Edmond, 1989), demonstrating that the canal is characterized by a lacustrine environment, with weak connection with the sea and weak tide effect. Moreover, McCulloch et al. (1989) suggested that if ΔSr is greater than 12.2, it is reasonable to judge it as a typical lacustrine environment. $^{87}Sr/^{86}Sr$ ratios for seven samples from Xiaodukou are within the range of 0.71105 – 0.71274 (Table 1), significantly higher than the values of contemporary seawater: 0.709087 – 0.709147 (Hodell et al., 1990), also higher than the average value of modern Yellow River: 0.7111 (Plamer and Edmond, 1989). So, for the environment where Xiaodukou foraminifera lived, the strongly marine environment connected with the sea can be completely excluded, but, is it possible to represent a weakly marine environment with low salinity and weak connection with the sea? Considering the two-component model of seawater mixture with river and lacustrine water, calculations completed by the author and the research results of McCulloch et al. (1989) and De Deckker (1988) manifested that the value of ΔSr is negatively proportional to salinity in the system. If seawater 300 km far from the Xiaodukou area entered the ancient Nihewan Lake through the tectonic "channelways", the salinity of ancient Nihewan lacustrine water should be lower than that of Luchaogang water: 1.36 because the ΔSr values of Xiaodukou foraminifera are within the range of 27.3 – 51.5 (Table 1), larger than those of Luchaogang samples. However, carbon isotope analysis of Xiaodukou foraminifera showed that the salinity of foraminifera-inhabitant environment was larger than 20‰ (Wu Nanqing, 1993), with pH = 8 – 9 (Chen Maonan et al., 1988). On the other hand, regionally geologic field work available also gives no plausible evidence to explain how the ancient Nihewan Lake 300 km far from the coastal line connected with the sea from the viewpoint of tectonics (Chen Maonan et al., 1988). In the last decade some findings about modern foraminifera species existing in inland salt-water, brackish-water lakes without any relation to the sea have been reported and demonstrated that it is highly possible that some foraminiferal species, which can tolerate the environment extremely deviated from the normal sea, inhabit an inland lake. More evidence came from the detailed analysis of $^{87}Sr/^{86}Sr$ ratios in Xiaodukou foraminifera and field geology. $^{87}Sr/^{86}Sr$ ratios in samples X-J-29 and X-J-15 located at the bottom of the foraminiferal fossil-bearing strata are higher than those of the other samples, implying that great environmental changes in the ancient Nihewan Lake could have taken place during the time of appearance of foraminifera. It is usually accepted that $^{87}Sr/^{86}Sr$ ratios in a lake depend on the ages and Rb/Sr ratios of different types of bed rocks and overlying sediments, and rivers from different areas in a basin are completely mixed and isotopes in the lake are uniform (Neat et al., 1979). So, $^{87}Sr/^{86}Sr$ ratios in a lake are comparatively constant, but, when it undergoes strong evaporation or tectonic uplifting or both, the lake could be thereafter divided into some small lakes, and Sr isotopic ratios in the lake could vary significantly because of great differences in regional material source. As one of the depositional centers in the ancient Nihewan Lake, in the 28th bed at Xiaodukou there exist gravels and coarse sands at the bottom, in going upwards the sands become finer and finally as fine as muddy silt and clay in size (Fig. 1), which really reflects the change trend of lacustrine level: from low to high and probably caused by tectonic activity. Because the salinity of Xiaodukou foraminifera-inhabitant environment is larger than 20‰, much higher than that of the lake earlier and later (Wu Nanqing, 1993), if there only occurred tectonic uplifting and no change in climatic condition, it is impossible to cause high salinities in the lake. Only through the process of strong evaporation would the lacustrine level and salinity of the lake become lower and higher respectively and the regional salt-water or brackish-water lacustrine environment be produced. Such a lacustrine environment is suitable for the inhabitance of foraminifera. So, it is reasonable to conclude that Xiaodukou foraminiferal fossil assemblages belong to non-marine foraminiferal species.

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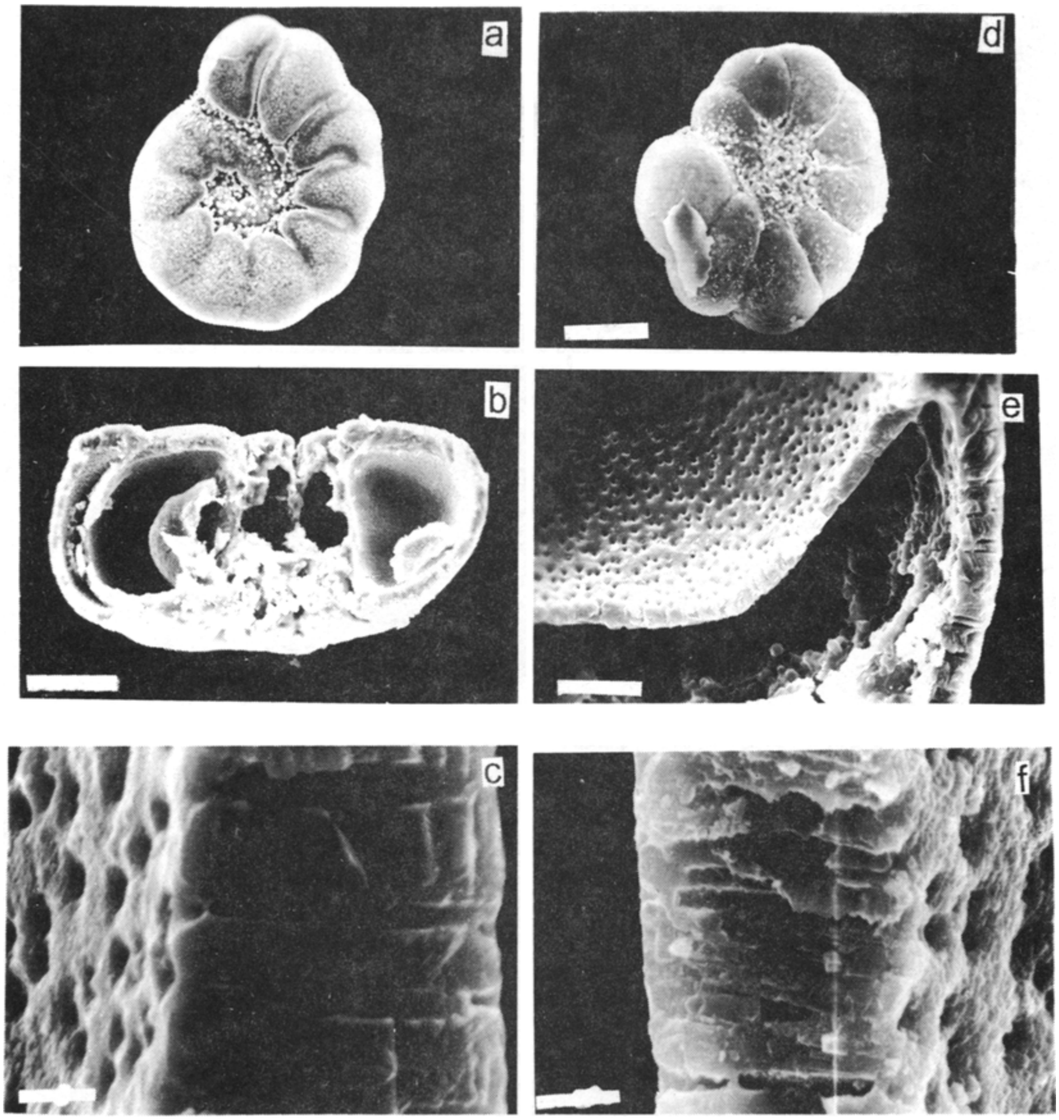

Photo 1 (a − f). SEM photos of "*Nonion shansienses*" modern species, Luchaogang, Shanghai: a. Overall SEM photo (× 200, scale bar = 100 μm); b. intersect SEM photo (× 450, scale bar = 50 μm); c. microarea SEM photo of chamber wall structure (× 10000, scale bar = 2 μm); SEM photo of "*Nonion shansienses*" of Sample X-J-29, Xiaodukou section; d. overall SEM photo (× 350, scale bar = 50 μm); e. partial intersect SEM photo (× 2000, scale bar = 10 μm); f. microarea SEM photo of chamber wall structure (× 8000, scale bar = 2.5 μm).