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A heavy mineral viewpoint on sediment provenance and environment in the Qiongdongnan Basin

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Abstract

Based on heavy mineral data in core samples from eleven drillings, supplemented by paleontological, element geochemical and seismic data, the evolution of sediment provenance and environment in the Qiongdongnan Basin (QDNB) was analysed. The results show that the basement in the QDNB was predominantly composed of terrigenous sediments. Since the Oligocene the QDNB has gradually undergone transgressions and evolution processes in sedimentary environment from terrestrial-marine transitional to littoral-neritic, neritic, and bathyal roughly. The water depth showed a gradually increasing trend and was generally greater in the southern region than that in the northern region in the same time. With changes in sedimentary environment, provenances of the strata (from the Yacheng Formation to the Yinggehai Formation) showed principal characteristics of multi-sources, evolving from autochthonous source, short source to distant source step by step. During the Early Oligocene, the sediments were mainly proximal basaltic pyroclastic source and adjacent terrigenous clastic source, afterwards were becoming distant terrigenous clastic sources, including Hainan Island on the north, Yongle Uplift on the south, Shenhu Uplift on the northeast, the Red River System on the northwest and Indochina Peninsula on the southwest, or even a wider region. The Hainan Island provenance began to develop during the Early Oligocene and has become a main provenance in the QDNB since the Middle Miocene. The provenances from Yongle Uplift and Shenhu Uplift most developed from the Late Oligocene to the Early Miocene and gradually subsided during the Middle Miocene. During the Late Miocene, as a main source of sediments filled in the central canyon, the Red River System provenance added to the QDNB massively, whose impact terminated at the end of the Pliocene. The western Yinggehai Basin (YGHB) provenance derived from Indochina Peninsula had developed from the Pliocene on to the Pleistocene. In addition, the material contribution of marine authigenous source to the basin (especially to the southern region) could not be ignored.

Key words: heavy minerals, provenance, sedimentary environment, Qiongdongnan Basin, northern South China Sea

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1 Introduction

Sediment provenance and environment analysis, as an important part of sedimentary basin analysis, is an important basis for paleogeomorphic remodeling, lithofacies paleogeographic reconstruction, ancient sedimentary route reproduction, tectonic background analysis, source rock tracking, paleoenvironmental and paleoclimatic recovery, underground stratigraphic correlation and reservoir prediction (Zhao and Liu, 2003; Weltje and Hilmar, 2004; Cao et al., 2013; Yang et al., 2013), which is of great significance in oil and gas exploration. At present, both at home and abroad, many methods have been employed in the research of sediment provenance analysis, including sedimentology, petrology, heavy mineralogy, element geochemistry, geochronology, geophysics, clay mineralogy and microfossils, and so on (Yang et al., 2013), in which heavy mineral analysis has proven an effective way of tracing provenance.

On sediment provenance and environment study in the Qiongdongnan Basin (QDNB), current publications are mostly restricted to the shallowwater area, in which the strata involved are not systematic, the regional drilling-tie correlation is lacking, and in particular the study on the southern deepwater area is in extremely low degree. In this paper, heavy mineral assemblages in core samples from two latest drillings in the deepwater area were identified, available heavy mineral data of shallowwater drillings were collected, and source-sensitive indicators such as terrigenous stable heavy minerals and ZTR index (total abundances of zircon, tourmaline and rutile) as well as several environment-indicating authigenous heavy mineral indexes were extracted. Based on heavy mineral data, supplemented by paleontological, element geochemical and seismic data, the evolution of sediment provenance and environment in the basement, Yacheng Formation, Lingshui Formation, Sanya Formation, Meishan Formation, Huangliu Formation, Yinggehai Formation and Ledong Formation in the QDNB was systematically analysed,

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which is expected to be rewarding for scientific research and oil and gas exploration.

2 Geological background

The QDNB (Fig. 1) is located on the northwestern passive continental margin of the South China Sea, neighboring Hainan Uplift on the north, Yinggehai Basin (YGHB) on the west, Shenhu Uplift on the northeast, Yongle Uplift on the south, overall orientating NE–SW, with length of 250–450 km E–W, width of 150–200 km N–S, total area of 7×10^4 km^2, and maximum water depth of 3 km, which is a hydrocarbon-rich Cenozoic extensional rifted basin developed on a pre-Paleogene basement (Wang, 2012; Xu et al., 2012).

The tectonic framework of the QDNB is specifically characterized by “belts in the N–S direction and blocks in the E–W direction”. The so-called “belts in the N–S direction” refers that geologically the QDNB can be divided into five first-order tectonic units, respectively the northern depression belt, central uplift belt, central depression belt, southern uplift belt and southern depression belt, which can be further divided into secondary tectonic units, including 12 sags and seven uplifts and low uplifts (Ren et al., 2014; Wang et al., 2014a) (Fig. 1). The “blocks in the E–W direction” represents that the QDNB can be divided into eastern and western extension zones which are separated by NW faults between Lingshui Sag and Songnan Sag in the central basin (Lei et al., 2011).

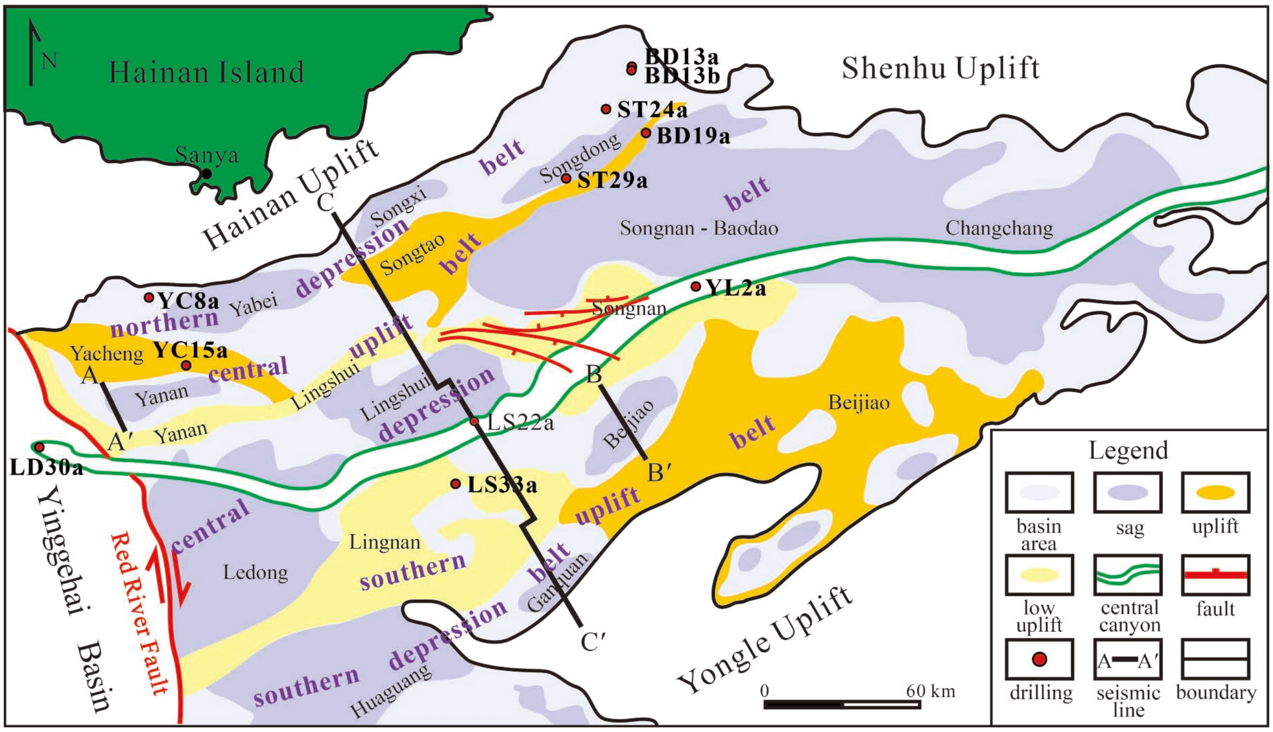

Fig. 1. Division of tectonic units and distribution of drillings in the QDNB.

The basement in the QDNB consists of the pre-Cenozoic igneous, metamorphic and sedimentary rocks. The filling sequences are dominantly composed of the Cenozoic strata, which comprise the Eocene series, Oligocene Yacheng and Lingshui Formations, Miocene Sanya, Meishan and Huangliu Formations, Pliocene Yinggehai Formation, and Quaternary Ledong Formation from bottom to top in order. The QDNB shows a typical passive continental margin feature of double-layer structure, fracture downward and depression upward (Taylor and Hayes, 1983). Two tectonic evolutionary stages, syn-rifting and post-rifting (Gong et al., 1997), have been identified, according to an angular unconformity corresponding to the T60 seismic reflection. The two stages have been further subdivided into four substages, faulting, faulting-depressing, post-rifting thermal subsidence and post-rifting accelerating subsidence, in accordance with the T70 and T30 seismic reflections (Lei et al., 2011; Ren et al., 2014). Recent studies (Wang et al., 2011a; Jiang et al., 2014; Ren et al., 2014; Wang et al., 2014a; Wang et al., 2014b) have indicated that the QDNB is of bright exploration prospecting for its two sets of major source rocks, several sets of good reservoir-caprock associations, favorable hydrocarbon migration conditions and multi-trap types.

In recent years, many researchers (Yao et al., 2008; Chen et al., 2010; Shao et al., 2010; Bai et al., 2011; Wang et al., 2011b; Cao et al., 2013; Li et al., 2014) have devoted to the study on the sediment provenance and environment evolution in the QDNB. The results indicate that there have developed many sediment sources in the QDNB such as Hainan Island on the north, Yongle Uplift on the south, Shenhu Uplift on the northeast, the Red River System on the northwest, Indochina peninsula rivers on the southwest, local eroded uplifts within the basin and authigenous sediments, and so on, and that with an overall gradually increasing water depth, there have developed varied and complicated sedimentary environments in the QDNB, evolving gradually from marine-terrestrial transitional during the Early Oligocene to bathyal during the Quaternary. Some researchers (Lin et al., 2001; Su et al., 2009, 2013, 2014; Yuan et al., 2010; Gong et al., 2011; Li et al., 2011; Wang, 2012; Xie et al., 2012a; Xu et al., 2012; He et al., 2013; Li et al., 2013a, b) focused on the provenance study of the central canyon system, pointing out that the sediments filled in the central canyon came from Hainan Island, the Red River System and western YGHB. Bai et al. (2011) systematically analysed the provenance of the 3rd member of the Oligocene Lingshui Formation in the YC13-1 gasfield located in the northwest corner of Yanan Sag using multi-methods of heavy minerals, paleogeomorphology, composition and structure of lithic fragments and dip logging, concluding that the provenance was Hainan Island on the northwest. Wang et al. (2011b) discovered a huge "Red River submarine fan" on the basis of seismic and borehole data, which is located in the binding site of the YGHB and QDNB and was developed during the Late Miocene, analysed heavy mineral assemblages of drilling YC35-1-1 located on this fan, and inferred that the source of this fan is the Red River System. Cao et al. (2013) made a conclusion that the QDNB has developed the Hainan Island provenance since the Early Miocene, and was contributed by the Red River System provenance during the Late Miocene and the western YGHB provenance during the Pliocene, based on the study of heavy mineral data in the Neogene strata of shallowwater drillings.

In summary, numerous studies have been done on the evolution of sediment provenance and environment in the QDNB, in which abundant meaningful results have been obtained. However, there remain lots of unsolved problems, for example, the comprehensively regional correlation between multi-drillings is lacking and the wide regional conclusion is not clear.

3 Materials and methods

Heavy minerals in core samples from two deepwater drillings LS33a and LS22a were specifically identified in this paper. Moreover, heavy mineral data in core samples from another nine drillings including shallowwater drillings BD13a, BD13b, BD19a, ST24a, ST29a, YC8a, YC15a and LD30a and a deepwater drilling YL2a were provided by Zhanjiang Branch of CNOOC Ltd. (Fig. 1). The strata encountered by above drillings involve the basement, Yacheng Formation, Lingshui Formation, Sanya Formation, Meishan Formation, Huangliu Formation, Yinggehai Formation and Ledong Formation.

Heavy minerals are such minerals with small particles, higher specific gravity than 2.86 g/cm^3, stable chemical properties, and strong weather resistance, whose mass fractions are usually less than 1% in sedimentary rocks. Morton (1985) concluded that heavy minerals in the 63–125 μm grain-size fraction are most abundant and can be considered as a representative of heavy mineral assemblages in the whole grain-size fraction. Therefore, the 63–125 μm fraction is usually selected for provenance analysis.

Heavy mineral analytical method is as follows: First, samples were processed to remove oils mixed into by drilling additives, using soxhlet extractor "organic distillation extraction" (oils can be cleared away completely after 20.5 h). Then, the 63–125 μm fraction was screened out, washed with deionized water, dried in low temperature (<60°C), and then separated into light and heavy minerals in bromoform solution (2.80 g/cm^3) using the funnel technique. The separated heavy minerals were washed 2–3 times with absolute ethyl alcohol, dried in constant temperature (60°C), mounted on glass slides and identified using stereomicroscope and polarizing microscope. At least 300, whenever possible, more than 600 heavy minerals were identified and counted from each slide, which is a sufficient number for characterizing abundances of common species. The species particle percentage was obtained by calculating. The preprocessing of samples was finished in Key Laboratory of Submarine Geosciences and Prospecting Techniques, Ministry of Education, Ocean University of China. The mineral separation and identification were accomplished in Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences.

4 Heavy mineral assemblages

Heavy minerals in sediment cores from drillings in the QDNB comprise terrigenous and authigenous components, in which the former is dominated by zircon, tourmaline, garnet, epidote group, magnetite, limonite, leucosphenite, hornblende, rutile, and mica group, and the latter is composed of pyrite, barite, dolomite, sphalerite, and glauconite. Heavy mineral abundances are listed in Table 1. In north drillings, heavy minerals are predominantly terrigenous (average percentage of 65%), and authigenous minerals are relatively less, while in south drillings, dominant minerals are authigenous (approximately 95%) (Fig. 2), which suggests that there was a dominant terrigenous material contribution to the northern part of the QDNB and a significant authigenous material contribution to the southern part.

In the strata, terrigenous heavy mineral assemblages are basically unchanged, but there exist large differences in abundance (Fig. 3), which may suggests that there exist differences in the distance between the source area and drilling locations. Drillings with similar heavy mineral assemblages can be divided into five groups, drillings BD13a, BD13b, BD19a, ST24a and ST29a, drillings YC8a, YC15a and LD30a, drilling YL2a, drilling LS22a and Hainan Island rivers, and drilling LS33a (Fig. 3).

5 Provenance and environment analysis

Terrigenous stable heavy minerals and their assemblages, which are restricted to specific source rocks and are sensitive indicators of provenance (Morton, 1985; Hallsworth et al., 2000; Yue, 2010; Morton et al., 2011; Sevastjanova et al., 2012; Cao et al., 2013; Wong et al., 2013; Jafarzadeh et al., 2014; Olivarius et al., 2014), are widely used in provenance discriminating, for example, generally along the flow direction, the farther away from the source area, the greater the relative contents of zircon, tourmaline, magnetite, leucosphenite and ZTR. Authigenous heavy minerals are of certain indicating significance to environmental changes. Authigenous pyrite, whose value is normally positively correlated with water depth, is generally formed in a reducing environment in deep water. Sedimentogenic dolomite usually represents a very shallow and strong evaporitic environment (Wang et al., 2013). Barite is common in muddy and sandy sediments in shallow-marine area, reflecting a littoral-neritic environment.

Heavy mineral assemblages in sediments are constrained by many factors, including mainly source rock type as well as burial diagenetic dissolution and hydraulic sorting. Previous studies (Shields and Stille, 2001; Liu et al., 2006; Li et al., 2007; Miao et al., 2008) proved that the better the correlation between δCe and δEu, the greater the influence of diagenesis on sediment samples. As can be seen from Fig. 4, there is a poor correlation between δCe and δEu in strata in drilling LS22a (correlation coefficient R^2=0.01–0.02) as well as in drilling LS33a (R^2 maximum of only 0.55), indicating that the impact of diagenesis on sediments in the deepwater area can be negligible. In consideration of that the stratigraphic thickness in the shallowwater area is far less than that in the deepwater area during the same period, the impact of diagenesis on heavy mineral assemblages of shallowwater drillings can be negligible as well.

Value plane distribution of heavy minerals in each sediment-

Fig. 2. Particle percentages of authigenous heavy minerals in sediment cores from drillings in the QDNB. Fm. denotes Formation. The same below.

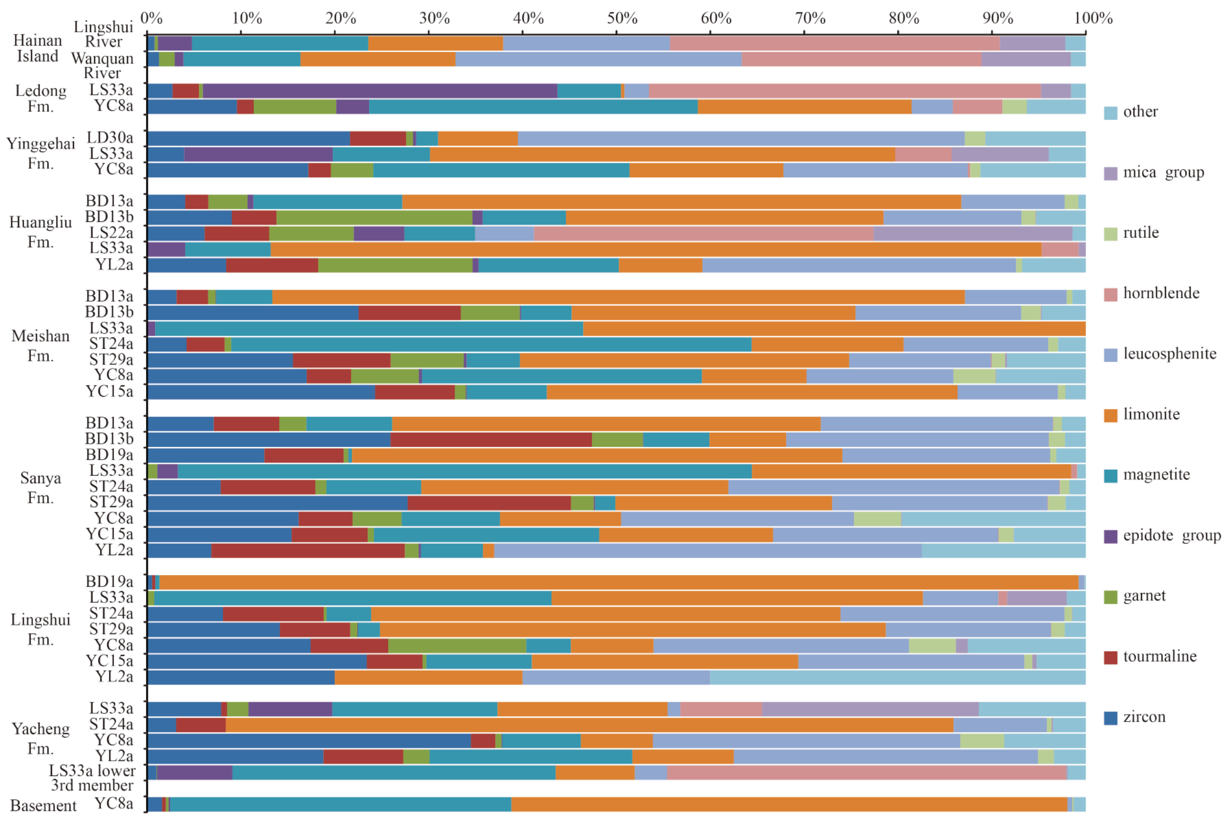

Fig. 3. Particle percentages of terrigenous heavy minerals in sediment cores from drillings in the QDNB.

ary period was made by using four kinds of terrigenous stable heavy minerals (zircon, tourmaline, magnetite, and leucosphenite) and ZTR index. Q-type cluster analysis of drilling assemblages was done by data of thirteen significant heavy mineral species (zircon, tourmaline, garnet, epidote group, magnetite, limonite, leucosphenite, hornblende, rutile, mica group, pyrite, barite, and dolomite) (using Ward method as clustering method and squared Euclidean distance as metric). Based on heavy mineral data, combined with paleontological, element geochemical and seismic data, the sediment provenance and environment evolution in the QDNB is discussed synthetically.

5.1 *Basement in pre-Paleogene*

The basement in the QDNB is composed of a double-layer structure with the Proterozoic strata as lower unit and the Palaeozoic strata as upper unit, devoid of the Mesozoic strata. The northern part of the basement is dominated by the Paleozoic sedimentary and epimetamorphic rocks, the southern part by the Proterozoic gneisses, and the eastern part by the Paleozoic metamorphic rocks (Lu et al., 2011). The sediment cores from drilling YC8a show that heavy minerals in the pre-Paleogene basement are predominantly terrigenous (approximately 92%, Table 1, Figs 2 and 5), of which the limonite and the magnetite are respectively up to 59% and 36% in abundance (Table 1, Fig. 3). Limonite is diagnostic of a sedimentary rock source, and the magnetite of a magmatic or metamorphic rock source. These indicate that source rock types revealed by heavy mineral data are consistent with regional sedimentary and epimetamorphic lithologies of the basement in the northwestern basin where drilling YC8a is located, suggesting that the QDNB was predominated by terrestrial facies deposition in the Late pre-Paleogene.

The Paleocene and Eocene strata were not encountered by any drilling, so the evolution of provenance and environment in these two strata is not discussed in this paper.

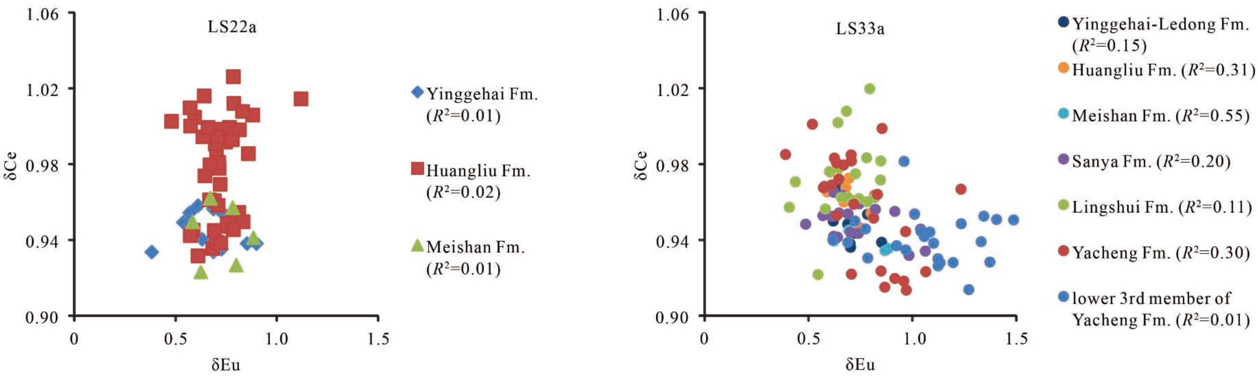

Fig. 4. Correlation analysis of δCe-δEu in sediment cores from deepwater drillings. Different from other formations, the lower 3rd member of the Yacheng Formation was mainly composed of pyroclastics, so it was drawn individually.

5.2 *Yacheng Formation in Early Oligocene*

The sediment cores from north and south drillings in the QDNB both have low values of zircon, tourmaline, leucosphenite and ZTR, and in the heavy mineral Q-type cluster analysis, south drilling LS33a has an alienated genetic relationship with north drillings (Fig. 6), jointly indicating that there developed two main provenances respectively on the north and south. The interpretations on seismic profiles (Fig. 7) respectively through Yanan Sag in the north and Beijiao Sag in the south show that during the Oligocene (T80-T60), controlled by abundant faults, there disorderly deposited predominant proximal materials in the QDNB. The provenance discrimination diagram (Fig. 8) of rare earth elements in sediment cores from drilling LS33a reveals that sediments in the lower 3rd member of the Yacheng Formation were predominantly basaltic clastics, which were probably products of volcanic eruption in the rifting process of the South China Sea, while sediments in the other upper strata were similar to properties of the upper continental crust and should be continental source, which is consistent with the element geochemical conclusion of Li et al. (2014) and Sun et al. (2014). The above evidence jointly indicates material contributions from different sources: proximal pyroclastic source and adjacent terrigenous clastic source in the early Early Oligocene and distant terrestrial sources from Yongle Uplift on the south and Hainan Island on the north since the late Early Oligocene.

Influenced by the South China Sea movement, the QDNB fell into faulting episode in syn-rifting stage, with frequent tectonic activities, intense volcanic activities, undulating landforms, and a coastal environment. Specific evidence (Shao et al., 2010) shows that there developed littoral plain–littoral system and littoral–low fan system respectively in the northern and southern area of the Ledong-Lingshui Sags, and fan delta deposition system in the northern and southeastern part of Lingshui Sag. In sediment cores from drilling YC8a, the content of terrigenous heavy minerals is high and the barite content in authigenous heavy minerals is high too and varies widely (Fig. 5), reflecting a wholly shallow water and intensely changing environment in the western Yabei Sag. Microfossil assemblages of drillings YC13-1-a2, YC13-1-2, YC19-1-1, YC8a and YC21-1-4 (Shao et al., 2010; Xie et al., 2012b) indicate that the western basin was in constantly deepening shallow water and had an environment evolving from paralic in the 3rd member of the Yacheng Formation to thalassic in the 1st member of the Yacheng Formation. Of drilling ST24a, the content of terrigenous heavy minerals is high and authigenous heavy minerals are almost pyrites with low content, reflecting that it was a littoral-neritic environment in the northern Songdong Sag too, which is in accordance with the regional characteristics in paleosedimentary environment, for example that it was mainly neritic facies deposition in the Songnan–Baodao Sags (Zhu et al., 2007). Data above indicate that it evolved from a terrestrial-marine transitional environment to be a littoral-neritic environment in the northern basin during the Early Oligocene. Of drilling LS33a in the southern region, terrigenous heavy minerals reduce from about 80% to 5% in content and the dolomite content in au-

Table 1. Abundances (particle percentages) of heavy minerals in sediment cores from drillings in the QDNB

Formation	Sample	Terrigenous heavy minerals and ZTR/%													Relative authigenous heavy minerals/%					
		Zircon	Tourmaline	Garnet	Epidote group	Magnetite	Limonite	Leucosphenite	Hornblende	Rutile	Mica group	Other	SUM	ZTR	Terrigenous	Pyrite	Barite	Dolomite	Sphalerite	SUM
Hainan Island	Lingshui river (6)	0.8	0.0	0.3	3.6	18.8	14.4	17.8	35.2	0.0	7.0	2.2	100	0.8	99.2	0.9	0.0	0.0	0.0	100
	Wanquan river (9)	1.3	0.0	1.7	0.9	12.5	16.5	30.5	25.5	0.0	9.5	1.6	100	1.3	99.7	0.3	0.0	0.0	0.0	100
Ledong Fm.	LS33a (3)	2.7	2.8	0.4	37.8	6.8	0.4	2.6	41.8	0.0	3.2	1.6	100	5.6	69.2	27.8	0.0	3.0	0.0	100
	YC8a (1)	9.6	1.8	8.8	3.5	35.0	22.8	4.4	5.3	2.6	0.0	6.3	100	14.0	53.2	2.2	44.3	0.0	0.3	100
Yinggehai Fm.	LD30a (26)	21.6	6.0	0.7	0.3	2.3	8.5	47.6	0.0	2.2	0.0	10.7	100	29.8	91.5	5.3	2.7	0.4	0.1	100
	LS33a (5)	4.0	0.0	0.0	15.8	10.4	49.6	0.0	6.0	0.0	10.3	4.0	100	4.0	5.8	94.1	0.0	0.2	0.0	100
	YC8a (2)	17.2	2.4	4.5	0.0	27.3	16.4	19.6	0.3	1.1	0.0	11.2	100	20.7	68.7	29.4	1.9	0.0	0.0	100
Huangliu Fm.	BD13a (3)	4.1	2.5	4.2	0.6	15.9	59.5	11.0	0.0	1.5	0.0	0.8	100	8.0	60.9	39.1	0.0	0.0	0.0	100
	BD13b (12)	9.1	4.8	20.9	1.1	8.9	33.8	14.7	0.0	1.5	0.1	5.3	100	15.3	61.9	32.0	5.2	0.7	0.2	100
	LS22a (30)	6.1	6.9	9.0	5.4	7.5	0.0	6.3	36.2	0.0	21.2	1.4	100	13.0	70.5	26.0	0.0	3.5	0.0	100
	LS33a (7)	0.0	0.0	0.0	4.1	9.1	82.1	0.0	4.0	0.0	0.8	0.0	100	0.0	4.7	95.3	0.0	0.0	0.0	100
	YL2a (3)	8.4	9.8	16.4	0.6	15.0	8.9	33.4	0.0	0.6	0.0	6.8	100	18.9	82.8	17.2	0.0	0.0	0.0	100
Meishan Fm.	BD13a (12)	3.2	3.4	0.8	0.0	6.0	73.8	10.8	0.0	0.6	0.0	1.4	100	7.1	74.7	24.9	0.2	0.0	0.1	100
	BD13b (5)	22.5	10.9	6.3	0.1	5.4	30.2	17.6	0.0	2.1	0.1	4.7	100	35.5	60.3	35.3	4.3	0.1	0.0	100
	LS33a (6)	0.0	0.0	0.0	0.9	45.6	53.5	0.0	0.0	0.0	0.0	0.0	100	0.0	6.8	93.2	0.0	0.0	0.0	100
	ST24a (2)	4.2	4.1	0.7	0.0	55.4	16.2	15.4	0.0	1.1	0.0	3.0	100	9.3	68.8	30.1	0.7	0.0	0.3	100
	ST29a (6)	15.6	10.4	7.8	0.3	5.7	35.1	15.1	0.1	1.4	0.2	8.4	100	27.4	53.3	44.8	1.5	0.1	0.3	100
	YC8a (7)	17.0	4.7	7.2	0.3	29.9	11.1	15.7	0.0	4.5	0.1	9.5	100	26.3	83.3	16.4	0.3	0.0	0.0	100
	YC15a (3)	24.3	8.5	1.2	0.1	8.5	43.7	10.7	0.0	0.8	0.0	2.2	100	33.6	69.0	27.8	2.8	0.4	0.0	100
Sanya Fm.	BD13a (19)	7.1	7.0	2.9	0.0	9.2	45.7	24.7	0.0	0.9	0.0	2.5	100	15.0	82.6	16.2	1.1	0.1	0.0	100
	BD13b (8)	25.9	21.5	5.4	0.0	7.0	8.2	28.0	0.0	1.7	0.0	2.2	100	49.1	76.7	21.7	1.3	0.2	0.1	100
	BD19a (11)	12.5	8.4	0.5	0.0	0.4	52.2	22.1	0.0	0.7	0.0	3.2	100	21.6	65.3	21.7	12.4	0.6	0.1	100
	LS33a (13)	0.0	0.0	1.1	2.2	61.1	34.0	0.0	0.6	0.0	0.0	0.9	100	0.0	6.7	90.6	0.0	2.7	0.0	100
	ST24a (14)	7.9	10.1	1.2	0.0	10.1	32.7	35.3	0.1	1.0	0.0	1.8	100	18.9	64.5	35.2	0.2	0.0	0.1	100
	ST29a (23)	27.8	17.4	2.4	0.1	2.2	23.1	23.0	0.0	1.9	0.0	2.2	100	47.0	76.6	22.9	0.3	0.2	0.1	100
	YC8a (10)	16.2	5.7	5.2	0.0	10.5	12.9	24.8	0.0	5.0	0.1	19.6	100	26.9	62.8	36.9	0.1	0.2	0.0	100
	YC15a (6)	15.4	8.1	0.7	0.0	24.0	18.5	24.0	0.1	1.6	0.0	7.7	100	25.1	54.6	45.0	0.3	0.1	0.0	100
	YL2a (2)	6.8	20.6	1.5	0.3	6.6	1.2	45.4	0.0	0.0	0.0	17.4	100	27.4	54.7	45.3	0.0	0.0	0.0	100
Lingshui Fm.	BD19a (18)	0.5	0.3	0.0	0.0	0.5	97.9	0.6	0.0	0.0	0.0	0.1	100	0.9	80.4	0.6	18.9	0.1	0.0	100
	LS33a (26)	0.0	0.0	0.8	0.0	42.3	39.6	8.0	0.9	0.0	6.4	2.0	100	0.0	3.2	58.7	0.0	38.2	0.0	100
	ST24a (23)	8.1	10.7	0.3	0.0	4.8	50.0	23.9	0.0	0.8	0.0	1.4	100	19.6	70.4	29.2	0.2	0.2	0.1	100
	ST29a (16)	14.2	7.5	0.8	0.1	2.3	53.9	17.6	0.0	1.4	0.0	2.3	100	23.1	58.7	39.1	1.3	0.8	0.1	100
	YC8a (17)	17.4	8.3	14.7	0.0	4.7	8.8	27.2	0.0	5.0	1.3	12.6	100	30.7	53.6	42.3	4.0	0.1	0.0	100
	YC15a (2)	23.4	6.0	0.4	0.0	11.2	28.4	24.1	0.0	0.9	0.5	5.3	100	30.2	51.0	48.8	0.1	0.1	0.1	100
	YL2a (1)	20.0	0.0	0.0	0.0	0.0	20.0	20.0	0.0	0.0	0.0	40.0	100	20.0	0.0	89.3	10.8	0.0	0.0	100
Yacheng Fm.	LS33a (38)	7.9	0.6	2.3	8.9	17.6	18.1	1.4	8.7	0.0	23.1	11.4	100	8.3	7.0	33.5	0.0	59.6	0.0	100
	ST24a (2)	3.1	5.3	0.0	0.0	0.0	77.5	9.9	0.0	0.5	0.2	3.5	100	8.9	73.0	26.3	0.2	0.5	0.1	100
	YC8a (22)	34.5	2.6	0.6	0.1	8.4	7.7	32.7	0.0	4.7	0.0	8.7	100	41.8	59.1	30.4	9.7	0.0	0.8	100
	YL2a (1)	18.8	8.5	2.8	0.0	21.6	10.8	32.4	0.0	1.7	0.0	3.4	100	29.0	58.6	40.7	0.8	0.0	0.0	100
LS33a lower 3rd member (26)		1.0	0.0	0.0	8.0	34.5	8.4	3.4	42.5	0.0	0.2	1.9	100	1.0	35.7	33.7	0.0	30.6	0.0	100
Basement	YC8a (2)	1.6	0.4	0.3	0.2	36.4	59.2	0.5	0.0	0.2	0.0	1.3	100	2.2	91.8	7.8	0.4	0.0	1.0	100

Notes: Data of heavy minerals in sediments from Hainan Island rivers were provided by Zhanjiang Branch of CNOOC Ltd.. Numbers in parentheses indicate sample numbers. Fm. denotes Formation.

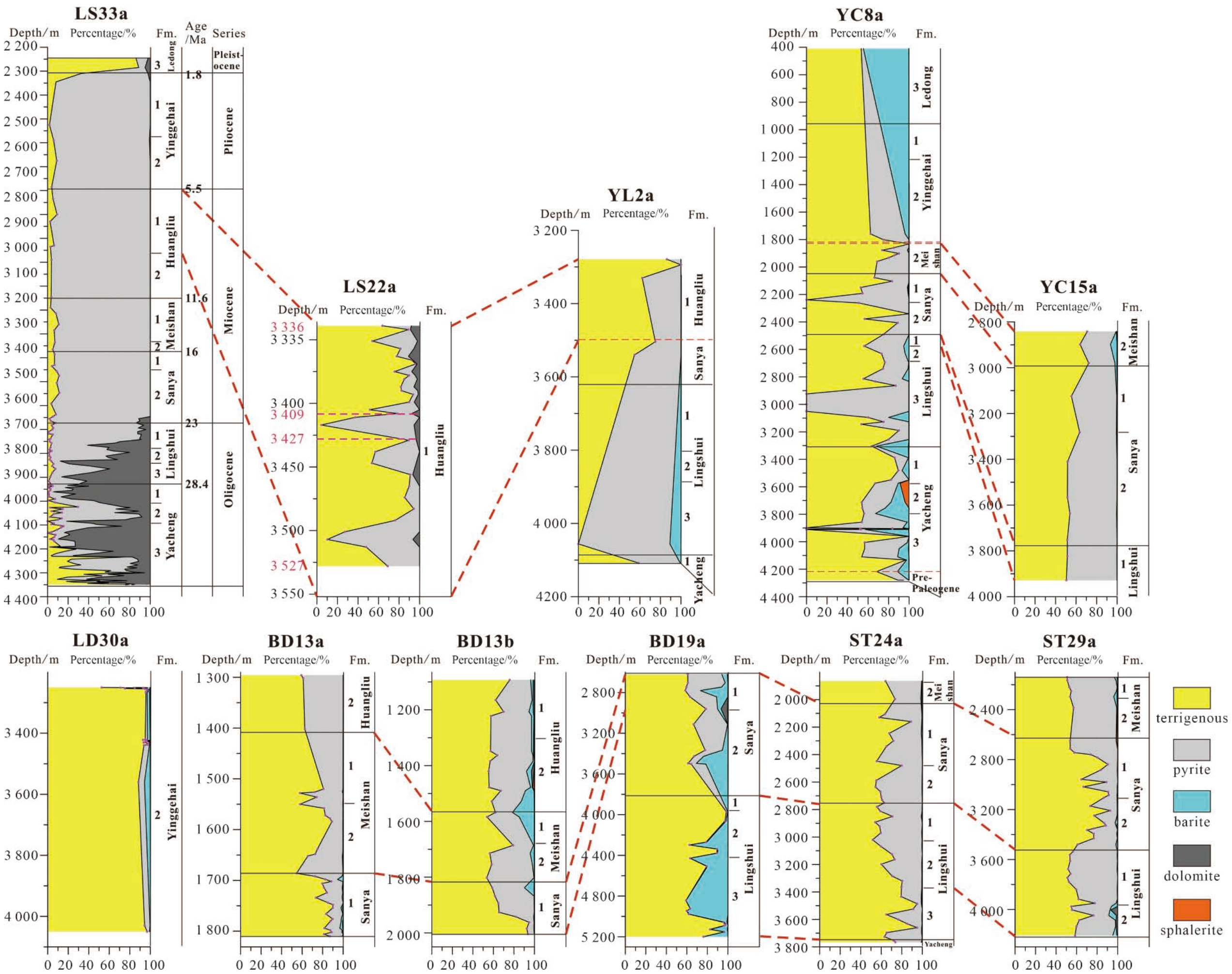

Fig. 5. Drilling-tie stratigraphic correlation of heavy minerals in sediment cores.

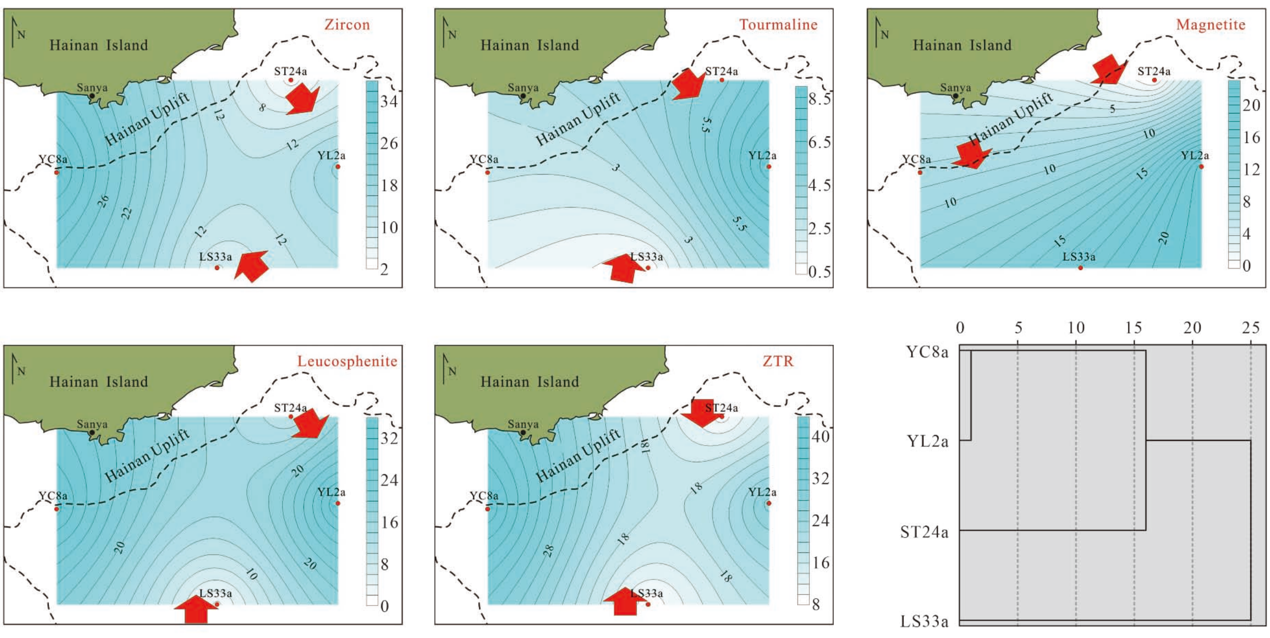

Fig. 6. Value plane distribution of terrigenous stable heavy minerals and ZTR, and the diagram of heavy mineral Q-type cluster analysis between drillings in the Yacheng Formation (except for the lower 3rd member of the Yacheng Formation). Red dots denote drilling locations. Red arrows indicate provenance directions. The same below.

thigenous heavy mineral assemblages is fluctuant and negatively correlated with pyrite, which indicate that the water depth was fluctuant correspondingly. Benthic foraminifera data of drilling LS33a show that the neritic species assemblage *Ammonia beccarii* var.—*Hanzawaia mantaensis* was dominant species, indicating a neritic environment. In addition, sediments from drilling LS33a had a general tendency of transitioning from proximal source to distant source and authigenous source, also reflecting an increasing water depth. Based on above evidence, it converted from terrestrial-marine transitional environment to littoral-neritic environment in the southern basin during the Early Oligocene.

5.3 *Lingshui Formation in Late Oligocene*

A similar provenance situation is probable during the Late Oligocene. There still developed two major sources: Hainan Island and Yongle Uplift (Fig. 9). Sediment cores from drilling BD19a have low values of zircon, magnetite, leucosphenite and ZTR, moreover, in the heavy mineral Q-type cluster analysis, drilling BD19a is alienated with other drillings, which jointly indicate that there added a new provenance to Baodao Sag (Fig. 9). During this period, affected by spreading of the South China Sea, an extensive transgression occurred in the whole basin and the seawater flowed into the QDNB in both east and west directions, inheriting transgressive directions during the Early Oligocene (Zhu et al., 2007; Zhang et al., 2009; Shao et al., 2010). Therefore, it can be interpreted as that the substance of Shenhu Uplift on the northeast began to input and became a new provenance to the basin.

Of authigenous heavy mineral assemblages in sediment cores

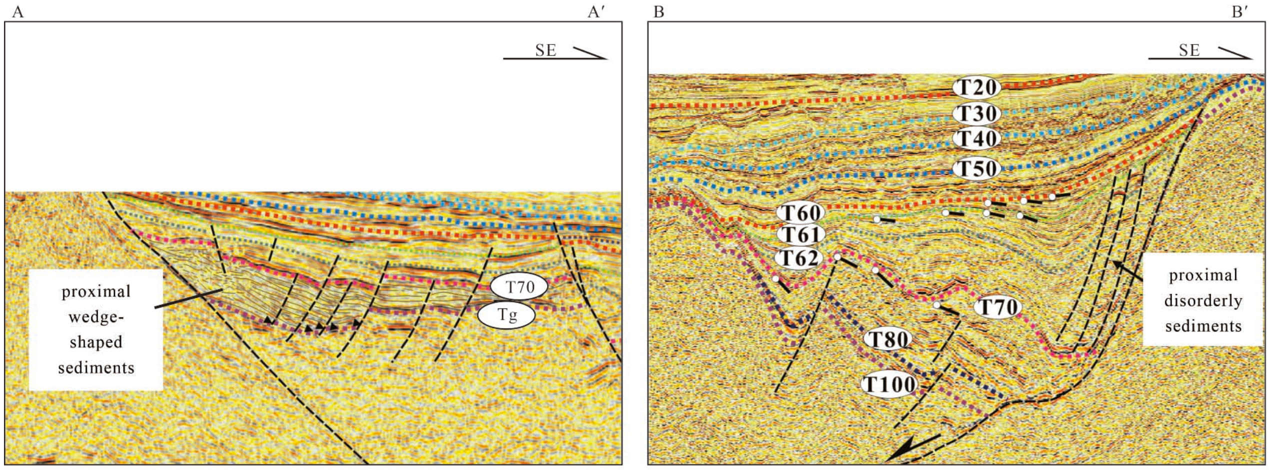

Fig. 7. Typical seismic profiles through the deepwater and shallowwater areas in the QDNB. Profile locations shown in Fig. 1.

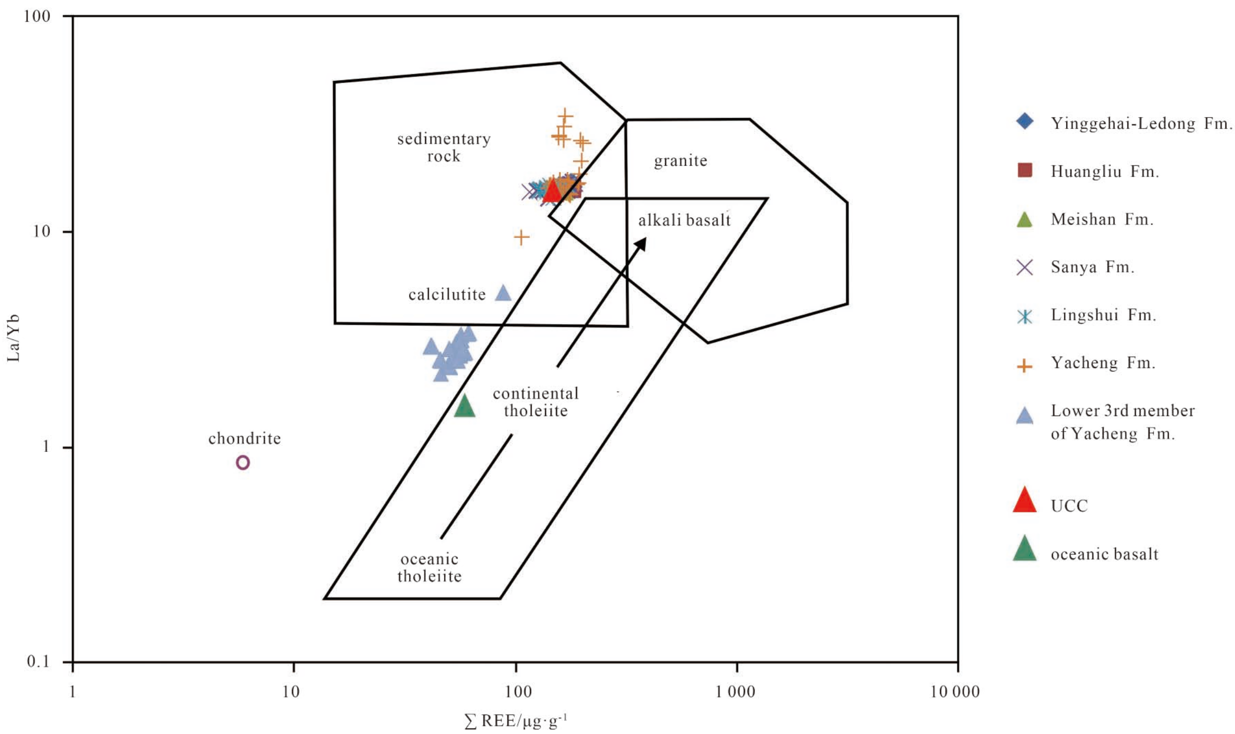

Fig. 8. Provenance discrimination of La/Yb-∑REE in core samples from drilling LS33a. REE denotes rare earth element. UCC (upper continental crust) data from Teng et al. (2004). Oceanic basalt data from Frey and Haskin (1964).

from drillings ST24a, ST29a, YC15a and YC8a, the pyrite is predominant and the barite is present in smaller amounts (Fig. 5), which reflect a neritic environment. The barite content is almost 100% in authigenous heavy mineral assemblages of drilling BD19a, reflecting a littoral-neritic environment. During this period, the environment evolved from inner neritic sea to middle neritic sea around drilling YC8a and from littoral sea to littoral-neritic sea around drilling BD19a (Xie et al., 2012b). A large number of marine microfossils were found in sediments from drillings LS4-2-1, ST24a, BD19a and BD20-1-1, indicating an entire marine environment (Shao et al., 2010). These above characteristics indicate that transgressions and neritic facies sediments emerged extensively and that a neritic environment occurred in the northern basin. The authigenous heavy mineral content in the Lingshui Formation is higher than that in the Yacheng Formation. Of drilling LS33a, the pyrite increases gradually from approximately 20% to 80% and the dolomite reduces gradually from approximately 75% to 10%, indicating a gradually increasing water depth. Of drilling YL2a, the pyrite varies in content between 60% and 90%, reflecting a great water depth. In the Lingshui Formation of drilling LS33a, the benthonic foraminifera population is more abundant both in variety and quantity than that in the Yacheng Formation and presents a very continuous distribution. Dominant species evolved from outer neritic species, for example *Ammonia indica* and *Florilus scaphus*, in the 3rd member of the Lingshui Formation, to be bathyal species, such as *Pullenia bulloides* and *Cibicidoides subhaidingerii*, in the 1rd member of the Lingshui Formation. These fossil evidence above indicates that there happened great changes in sedimentary environment and it had evolved to be an outer neritic-bathyal environment. These jointly indicate that there synchronously underwent transgression massively in the southern basin, and it transferred from littoral-neritic environment in the late Early Oligocene to be outer neritic-bathyal environment during the Late Oligocene.

5.4 *Sanya Formation in Early Miocene*

From the Early Miocene on, the QDNB has stepped into post-rifting subsidence stage in which the sedimentary environment tended to be stabilized and the provenance gradually evolved to be distant source (Fig. 7). During the Early Miocene, the QDNB had still three provenances: Hainan Island, Shenhu Uplift and Yongle Uplift (Fig. 10). According to the heavy mineral Q-type cluster analysis, drilling YL2a is closer to north drillings YC8a, YC15a, ST24a, BD13b and ST29a, indicating that the scope of the Hainan Island provenance had extended to the central depression belt where drilling YL2a is located. During this period, due to further increasing water depth, Shenhu Uplift was shrinking constantly (Cao et al., 2013), whose material contribution became less and less correspondingly. Of authigenous heavy minerals in sediment cores from drillings YC8a, YC15a, ST24a, YL2a, BD13b and ST29a, the pyrite is predominant while the barite is rare (Fig. 5), for drilling BD19a, in addition to barite, the pyrite emerges and presents an increasing trend from lower to upper strata, combined with the paleontological evidence (Xie et al., 2012b), a further increasing water depth and a middle-outer neritic environment in the northern basin can be inferred.

Of drilling LS33a, the dolomite disappears and the pyrite increases up to 90%, reflecting a large water depth and an environment tending to be stable in the southern basin. As for benthonic foraminifera fossils of drilling LS33a, bathyal species *Oridorsalis tenera, Karreriella bradyi* and *Cibicidoides subhaidingerii* are dominant species assemblages. The above information indicates that it had converted from outer neritic-bathyal environment to be bathyal environment thoroughly.

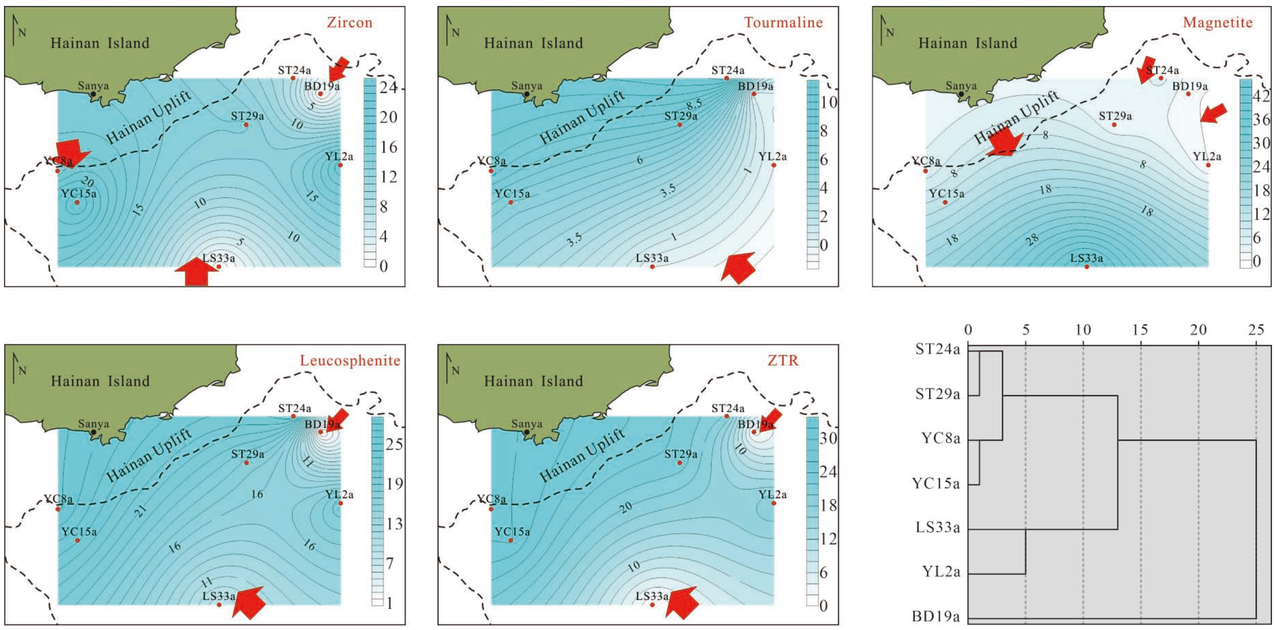

Fig. 9. Value plane distribution of terrigenous stable heavy minerals and ZTR, and the diagram of heavy mineral Q-type cluster analysis between drillings in the Lingshui Formation.

5.5 *Meishan Formation in Middle Miocene*

Inheriting the sedimentary framework during the Early Miocene, there still developed two provenances, respectively Hainan Island and Yongle Uplift during the Middle Miocene (Fig. 11). Due to the continuously increasing water depth, Shenhu Uplift was further shrinking (Cao et al., 2013), almost disappeared.

Recent studies (Xie et al., 2012b) showed that in the 2nd member of the Meishan Formation, the environment around drillings YC8a, LS4-2-1 and BD19a had been outer neritic, even up to be bathyal, however, to the 1st member of the Meishan Formation, the microfossil assemblages of these drillings are dominantly neritic species, indicating a regression. During the Middle Miocene, there contained pyrites in large amounts in sediment cores from north drillings YC15a, ST24a, ST29a and BD13b, indicating a great water depth. However, there also existed a very small amount of barites simultaneously. In the 1st member of the Meishan Formation, the barite amount has a sudden increase (Fig. 5), which reflects a decrease in water depth and probably a regression event in the South China Sea during the Middle Miocene (Qin, 1996). These show that during the Early Miocene, the water depth in the northern QDNB was increasing and the environment was outer neritic on the whole and even bathyal locally, to the Late Miocene, affected by the regression event in the South China Sea, the water depth decreased, but it remained an outer neritic environment.

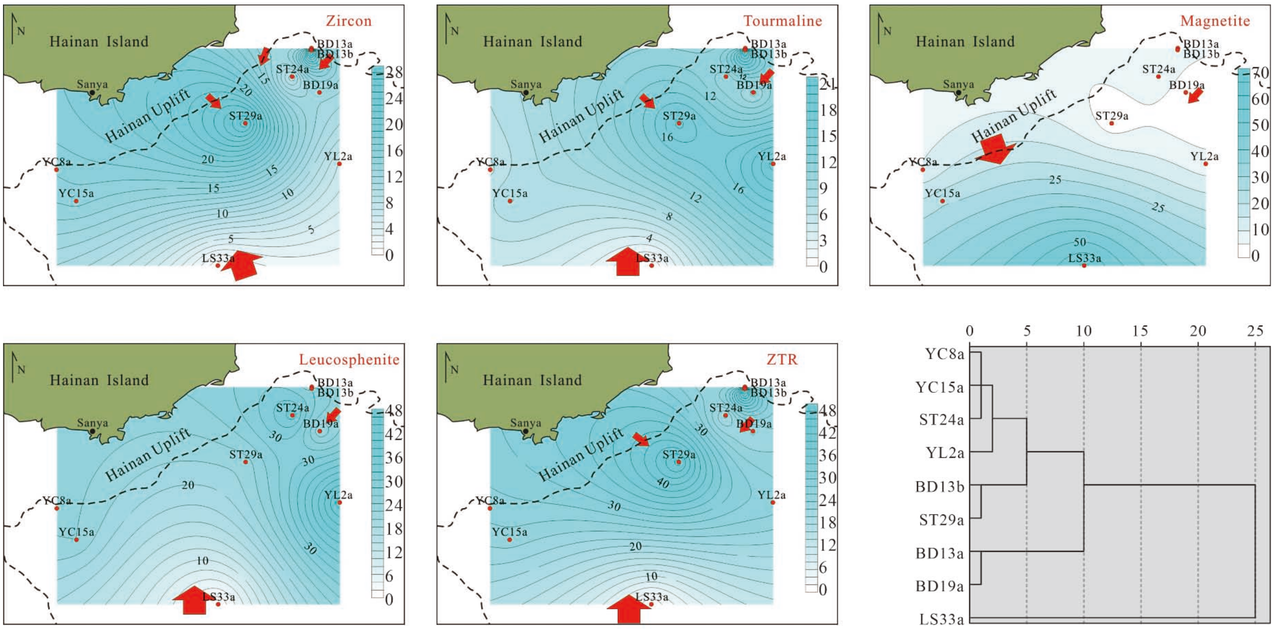

Fig. 10. Value plane distribution of terrigenous stable heavy minerals and ZTR, and the diagram of heavy mineral Q-type cluster analysis between drillings in the Sanya Formation.

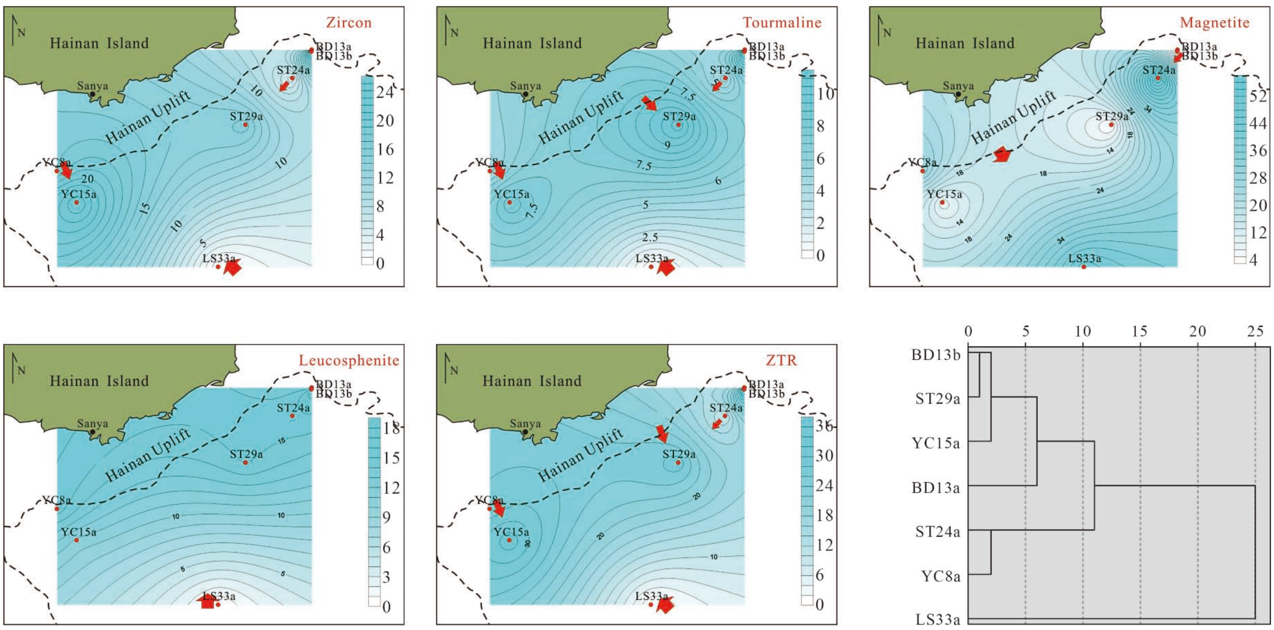

Fig. 11. Value plane distribution of terrigenous stable heavy minerals and ZTR, and the diagram of heavy mineral Q-type cluster analysis between drillings in the Meishan Formation.

In heavy mineral assemblages of drilling LS33a, the pyrite content is up to 90%, reflecting a large water depth and a stable sedimentary environment. In benthonic foraminifera fossil assemblages of drilling LS33a, the bathyal species *Sigmoilopsis* *schlumbergri* and *Planulina wuellerstorfi* are dominant species, indicating a continuous bathyal environment in the southern basin.

5.6 *Huangliu Formation in Late Miocene*

The ZTR plane distribution (Fig. 12) indicates that the Hainan Island provenance still developed. Heavy mineral assemblages between drilling LS22a and Hainan Island rivers are extremely similar (Fig. 3), indicating that the impact of the Hainan Island provenance had extended to the central canyon area where drilling LS22a is located. In regional seismic profiles oriented north-south through the QDNB (Fig. 13), there exist clear progradational reflection configurations nearby the shelf break in the northern basin and striking onlap structures in the vicinity of the T40 seismic discontinuity in the southern basin, indicating that since the Late Miocene (T40), the materials supplied by Hainan Island has increased suddenly in a large scale and pushed to south, locally even up to south boundary of the basin, and that the material contribution from Yongle Uplift on the south has decreased correspondingly, as well as the contribution from Shenhu Uplift. As above mentioned, the Hainan Island provenance has dominated the deposition in the whole basin since the Late Miocene.

The western central canyon started to develop during the Late Miocene (Fig. 13). From drilling LS22a to drilling YL2a in the plane, the value of both ZTR and terrigenous stable heavy minerals, for example zircon, tourmaline, garnet, magnetite, leucosphenite and rutile, increases more or less (Figs 12 and 14), while the content of unstable heavy minerals, for example epidote group, hornblende and mica group, decreases drastically (Fig. 14). In heavy mineral Q-type cluster analysis (Fig. 12), drillings LS22a and YL2a stay close. These above evidence jointly indicates that drillings LS22a and YL2a had a same provenance derived from the west. The 1st member of the Huangliu Formation in the central canyon system was encountered by drillings LS22a and YL2a both. There developed two sand bodies at the depth of 3 527–3 427 m and 3 409–3 336 m in drilling LS22a. Terrigenous heavy minerals in the two sand bodies have sudden increased values (Fig. 5) and present a positive correlation with the content of “sand” components, indicating a sandy sediment source for the 1st member of the Huangliu Formation. Previous studies (Su et al., 2009, 2013, 2014; Yuan et al., 2010; Li et al., 2011; Wang, 2012; Xie et al., 2012a; Xu et al., 2012; Zhao et al., 2012; Li et al., 2013a) have shown that during the Late Miocene, the Dongsha Movement caused a massive regression in the QDNB, as a result, the Red River System provenance prevailed in the central canyon system. As above mentioned, it can be concluded that during the Late Miocene, materials derived from the Red River System on the northwest were a major contribution to the QDNB.

Of authigenous heavy mineral assemblages in sediment cores

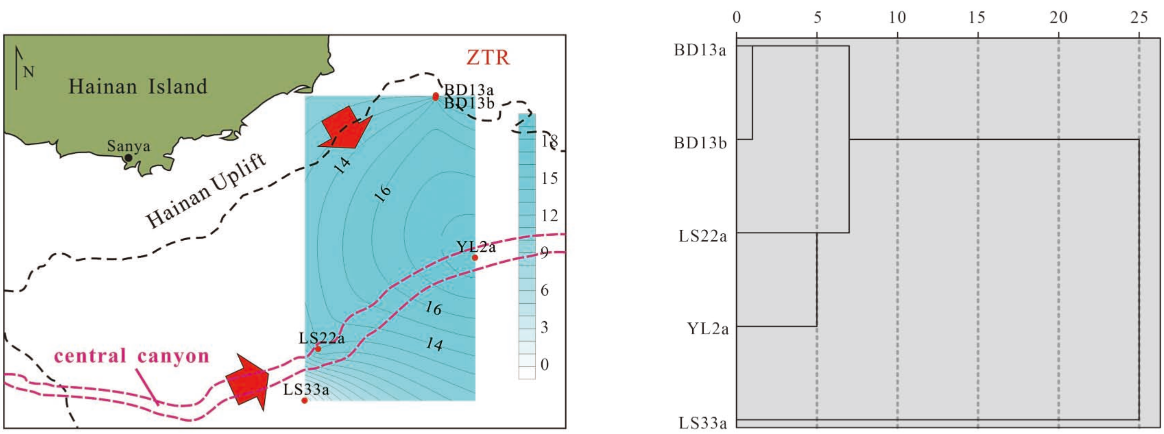

Fig. 12. Value plane distribution of ZTR, and the diagram of heavy mineral Q-type cluster analysis between drillings in the Huangliu Formation.

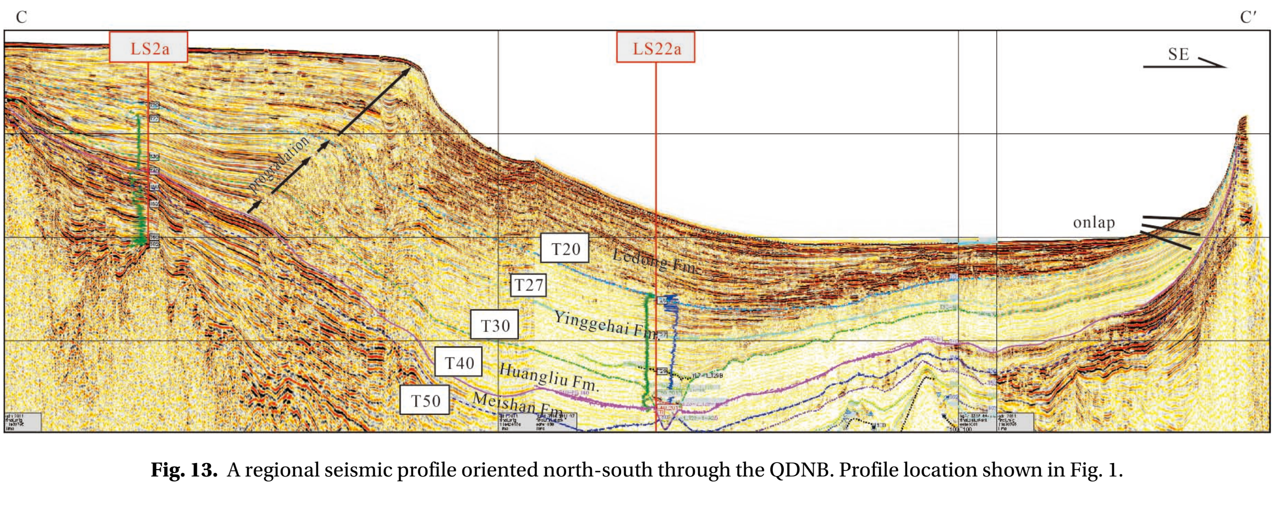

Fig. 13. A regional seismic profile oriented north-south through the QDNB. Profile location shown in Fig. 1.

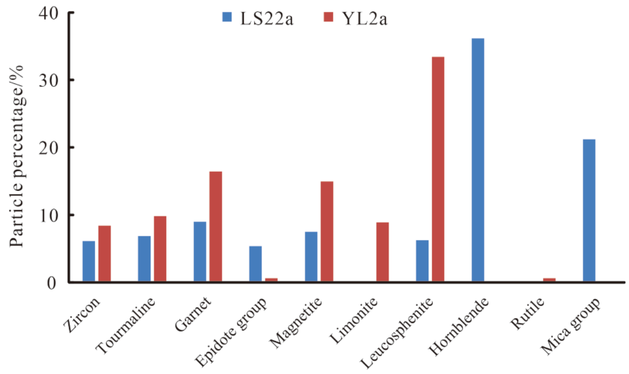

Fig. 14. Correlation of terrigenous heavy mineral assemblages in the 1st member of the Huangliu Formation from drillings through the central canyon.

from drillings BD13a, BD13b, LS22a and YL2a, the pyrite is predominant (Fig. 5), indicating a large water depth and a probable outer neritic-bathyal environment in the northern basin. Of drillings LS22a and YL2a, the content of terrigenous heavy minerals is high, significantly higher than that in the Sanya and Lingshui Formations (Fig. 5), which should be affected by the terrigenous inputs through the central canyon. Of drilling LS33a, authigenous heavy minerals are still almost pyrites, with a slightly higher content than that in the Meishan Formation (Fig. 5), and dominant species of benthonic foraminiferas are predominantly bathyal-abysmal agglutinate species, for example *Sigmoilopsis schlumbergeri* and *Ammodiscus argenteus*. These above characteristics indicate a bathyal-abysmal environment in the southern basin.

5.7 *Yinggehai Formation in Pliocene*

The information of sedimentology, seismic stratigraphy, geochemistry, heavy mineralogy and paleontology and so on (Li et al., 2011; Xie et al., 2012a; Cao et al., 2013; Li et al., 2013b) shows that during the Pliocene, the provenance contribution from Hainan Island was still large (Fig. 13) but the contribution from the Red River System became small, meanwhile, due to the recovery of rivers in the eastern Vietnam induced by the activating of the Red River fault zone, the western YGHB provenance derived from Indochina peninsula began to develop. Terrigenous heavy minerals of drilling LD30a in the Yinggehai Formation have a high average content of 91% (Table 1, Fig. 5), which could be a reflection of the large material inputs stemmed from the western YGHB. Because there were no great changes in tectonic setting, it was probably still a stable outer neritic-bathyal environment in the northern basin, inheriting the prior environmental characteristics during the Late Miocene. In sediment cores from drilling LS33a, the pyrite content is extremely high (Fig. 5), and dominant species of benthonic foraminiferas are predominantly bathyal species, for example *Planulina wuellerstorfi, Uvigerina peregrine* and *Bulimina marginata*, indicating a bathyal environment with great water depth in the southern basin.

5.8 *Ledong Formation in Pleistocene*

In sediment cores from drillings LS33a and YC8a, the contents of terrigenous components and the barite are high in the 3rd member of the Ledong Formation during the Pleistocene (Fig. 5). In seismic profiles (Fig. 13), the thickness of the Ledong Formation during the Quaternary decreases continuously from north to south, to be annihilated eventually. The above information indicates that there were massive materials transporting to the basin during the Pleistocene, which were predominately sourced from Hainan Island. About the sediment environment, a similar situation to that during the Pliocene is probable.

In conclusion, the evolution of sediment provenance and environment in the QDNB can be summarized as shown in Fig. 15. The basement was predominantly composed of terrigenous sediments. During the Early Oligocene, affected by large-scale faulting activities caused by the South China Sea movement, the provenance was mainly proximal pyroclastics and adjacent terrigenous clastics in early period and distant terrestrial materials from Yongle Uplift on the south and Hainan Island on the north in late period, and the sedimentary environment fluctuated frequently and evolved successively from terrestrial-marine transitional in early period to be littoral-neritic in late period. During the Late Oligocene, affected by spreading of the South China Sea, an extensive transgression occurred in the whole basin. Meanwhile, the Shenhu Uplift provenance joined on a large scale, with an outermost impact to the Songdong-Baodao Sags. It evolved to be a neritic environment in the northern basin and an outer neritic-bathyal environment in the southern basin. Since the Early Miocene, the QDNB has stepped into post-rifting subsidence stage, in which the water depth was further increasing and it evolved to be a middle–outer neritic environment in the northern basin. Moreover, the scope of the Hainan Island provenance increasingly extended to the central depression belt while Shenhu Uplift was constantly shrinking, whose material contribution to the basin decreased correspondingly. It evolved to be a bathyal environment thoroughly in the southern basin. During the Middle Miocene, it reached a bathyal environment in local northern basin, but to the late period, affected by the regression event in the South China Sea, the water depth had a slight decrease and it transitioned to be an outer neritic environment, meanwhile it was a stable bathyal environment all the time in the southern basin. From the Middle Miocene on, the Hainan Island provenance has become a dominant provenance in the basin while the impact of Yongle Uplift and Shenhu Uplift was weakening constantly. During the Late Miocene, the Dongsha Movement caused a massive regression in the QDNB, as a result, the Red River System provenance on the northwest began to add to the QDNB whose impact was mainly confined to the central canyon area and spanned up to the Yinggehai Formation in the Pliocene. During the Pliocene, the western YGHB provenance stemmed from Indochina peninsula developed. From the Late Miocene to the Pleistocene, it stabilized to be an outer neritic-bathyal environment in the northern basin and a bathyal environment in the southern basin.

6 Conclusions

(1) The basement in the QDNB was predominantly composed of terrigenous sediments. Since the Oligocene the QDNB has gradually undergone transgressions and it evolved to be a marine environment, with a generally increasing tendency in water depth. It possessed evolution processes in sedimentary environment from terrestrial-marine transitional to outer neritic-bathyal in the north, and from terrestrial-marine transitional to bathyal in the south on the whole.

(2) Provenances of the strata from the Yacheng Formation to the Yinggehai Formation showed principal features of multi-sources, evolving from autochthonous source, short source to distant source. During the Early Oligocene, the sediments were mainly proximal basaltic pyroclastic source and adjacent terri-

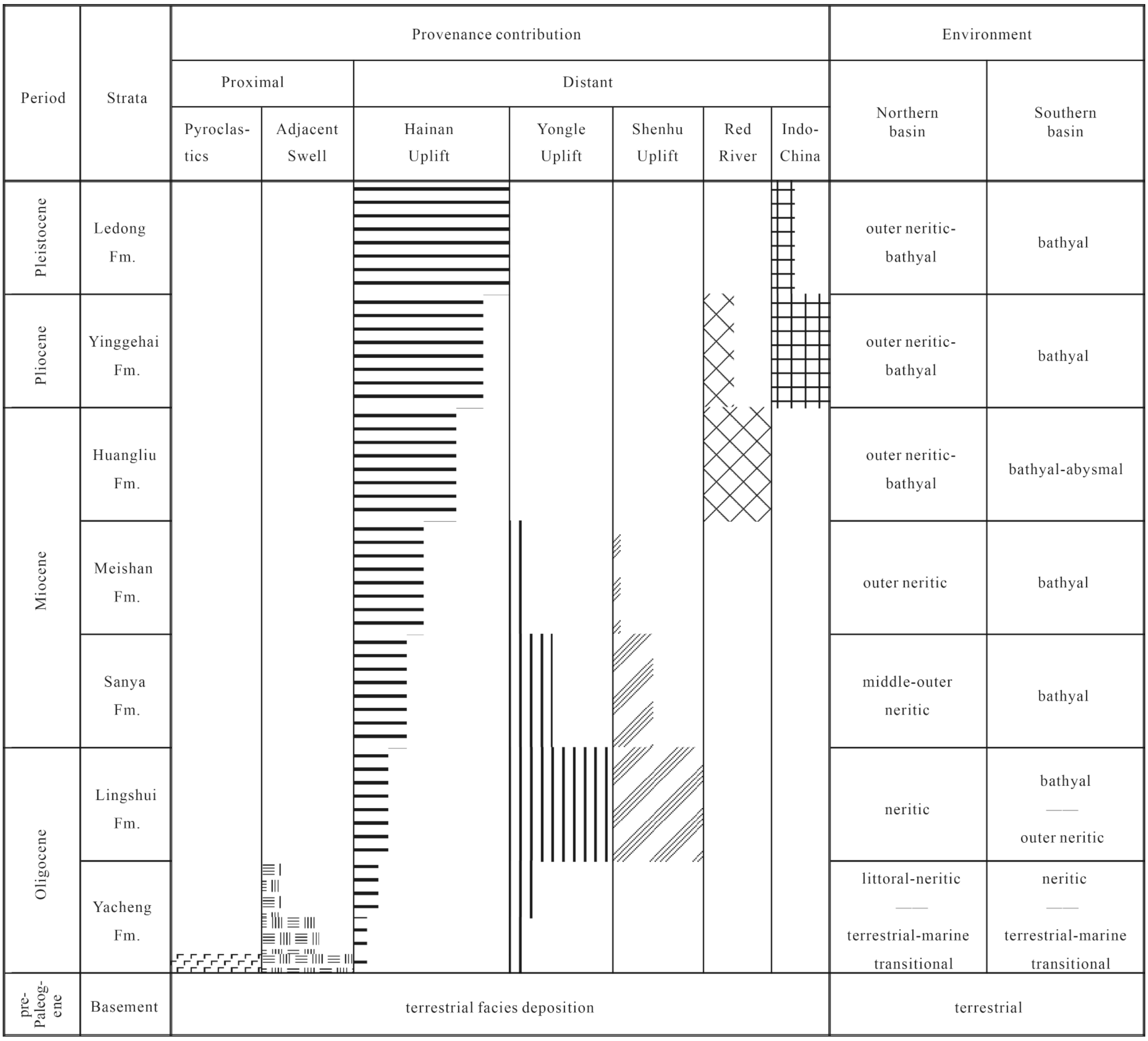

Fig. 15. Schematic diagram of sediment provenance and environment evolution in the QDNB.

genous clastic source, afterwards were becoming distant terrigenous clastic sources, including Hainan Island on the north, Yongle Uplift on the south, Shenhu Uplift on the northeast, the Red River System on the northwest and Indochina Peninsula on the southwest, or even a wider region. The Hainan Island provenance began to develop in the Early Oligocene and has become a main provenance in the QDNB from the Middle Miocene on to the present. The provenances from Yongle Uplift and Shenhu Uplift most developed from the Late Oligocene to the Early Miocene and gradually subsided during the Middle Miocene. During the Late Miocene, the Red River System provenance added to the central canyon region in the QDNB massively, whose impact terminated at the late Pliocene. The western YGHB provenance had developed from the Pliocene on to the Pleistocene. In addition, the material contribution of marine authigenous components to the basin (especially to the southern area) could not be ignored.

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