New Age for rift cessation across Pearl River Mouth Basin Evidence from Huizhou Sag, northern margin of South China Sea

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Abstract: Huizhou sag located at the northern part of Pearl River Mouth Basin (PRMB), South China Sea (SCS) is important for the study of rift evolution of Northern continental margin of South China Sea (NCMSCS). Previous rift system studies in the NCMSCS revealed age diachroneity both in the onset and cessation of rifting. Rifting started in the Late-Paleocene (~59) across the PRMB while rifting ceased at 32-30 Ma in the east, 28-27Ma in the western and 23.8 Ma at both north and south of central belt of PRMB. Recent re-interpretation of 2D seismic reflection data and well data across Huizhou sag provided by China National Offshore Oil Corporation (CNOOC) revealed a new age of rift cessation (16.5 Ma) for north central belt of PRMB. This observed inconsistency of maximum rifting age will no doubt impact extension tectonic modeling of the studied basin and affects basin subsidence partitioning between rift and thermal related mechanism.

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1. Introduction

Typically of other rifted margins, i.e Atlantic-type passive margins. The extensional basins in NMSCS show typical double-layer architecture (Zhou, D., et al. 1995) with regional unconformity interpreted as the breakup unconformity. The Lower sector is wedge-shaped syn-rift strata in restricted rifts, representing the crustal stretching during the rifting phase. The upper sector contains post-rift strata draping over the rifted topography, formed as a result of thermal cooling in the post-rifting phase.

Rifting and extensional tectonic of SCS has been extensively studied (Andrew Cullen et al., 2010; Ru, K. and J. D. Pigott 1986; Zhu, W. and C. Lei. 2013; Westaway, R. 1994; Harrison, Wenji et al. 1992; Zhou, D., et al. 1995; Zhu, W. and C. Lei. 2013) and three rift episodes have been documented; the Late cretaceous - Early Eocene (85-50 Ma), the Middle to late Eocene (50-40 Ma) and the Late Eocene -early to Late Oligocene (40-32 Ma or 23 Ma) Ru, K. and J. D. Pigott 1986 and Barckhausen, U., et al. 2014).

Work of Clift and Lin 2001 suggested 23.8 Ma as the age of extension termination across PRMB. Taking PRMB as a microcosm of SCS extension tectonic, the northern and southern central belt of PRMB are separated in terms of crustal extension scale and stretching intensity. Zhang, Y., et al. (2014) reported that, extension of the crust is inhomogeneous; fault patterns in continental shelf and slope are different The northern belt (shelf area) encompassing Huizhou sag has predominantly fault-dominated rift morphology, the southern belt (slope region) i.e Baiyun sag has both fault-dominated and magma-assisted rift morphology Chen L., (2014). Motivated by this, I tried to re-evaluate the rifting termination across the PRMB by observing the rifting phenomenon at the central part taking Huizhou sag as a case study. Through critical interpretation of the seismic section across the study area and review of existing literature new age is added to the rifting cessation already documented for the PRMB. It is impossible to generalize this outcome rather the objective is to present an updated view on the topic of rift evolution in the NMSCS

2. Regional Background

The South China Sea is one of the several major marginal sea basins in Southeast Asia. It is located tectonically at the junctions of the Indo-Australia plate, Eurasian plate and Pacific plate. The SCS is vital for the study of continental break-up and rifting especially for its lithosphere known to be warmer than usual compared to many classic Atlantic-type continental margin settings (Andrew Cullen et al., 2010) because horizontal extension of the lithosphere and its subsequent thermal cooling are responsible for the creation of many sedimentary basins (Cleotingh and Ziegler,2007). Cenezoic basins in northern shelf and slope of SCS all resulted from lithospheric extension, amongst which is the Pearl River Mouth Basin (PRMB), the Beibuwan Basin (BBWB), Yinggehai Basin (YGHB). Except for Qongdongnan Basin (QDNB) associated with a wrench motion along the Red River Fault. Zhou, D., et al. 1995.

The northern margin largest basin "Pearl River Mouth Basin (PRMB)" extends generally in NE-SW direction, about 800 km long in east-west direction with a total area of about 17.5×104 km (Fig. 1a). It has two sub-basins and three rises trending NE- ENE From north to south, these structures consist of the Northern fault terrace m, the northern subsidence zone including the Zhu 1 and Zhu 3 depressions, the central rise zone including Shenhu Rise, Panyu Low Rise and Dongsha Rise, the south subsidence zone including the Zhu 2 and the Chaosan depressions which straddle the shelf, the slope and the Southern rise (Fig. 1b). It became a passive margin during seafloor spreading of the SCS, from 32 Ma to 15 Ma (Taylor, B. and D. E. Hayes 1983; Briais et al., 1993) and also was considered to be non-volcanic passive margin for the lack of the landward flood basalts (X. Shi et al., 2005). The Huizhou sag lays in the central of Zhu 1 depression which is about 3.99x104km^2 as shown in Fig. 1b.

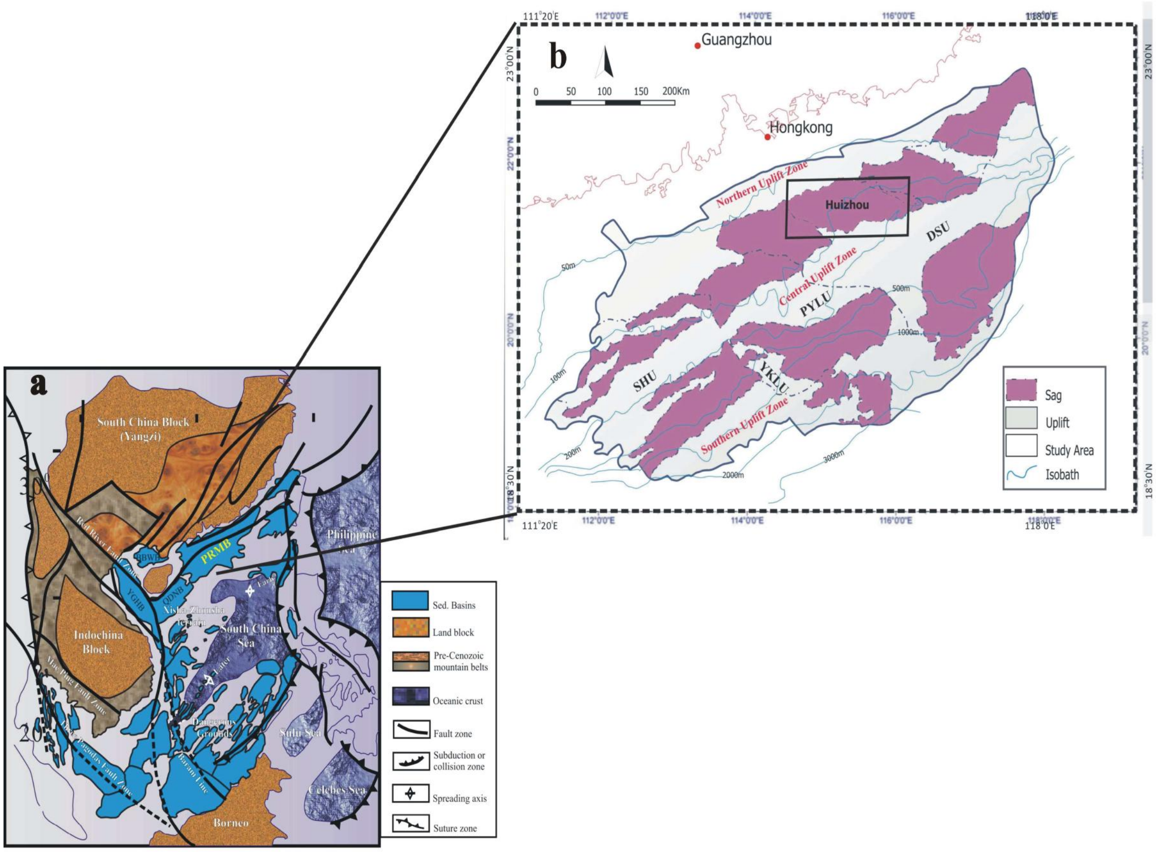

Fig1 (a) Map showing land blocks, major faults systems and distribution of Cenezoic sedimentary basins surrounding the SCS. Study area (PRMB) indicated in Yellow color texts. 2006. (b) Map showing Depressions and Uplifts in Pearl River Mouth Basin (PRMB), northern margin of the SCS. Depressions are represented by; Zhu 1, Zhu 2, and Zhu 3 and CSD (Chaoshan). The Uplifts are represented by; SHU. Shenhu uplift; PYLU. Panyu low uplift; DSU. Dongsha uplift; YKLU. Yunkai low uplift; The area marked in rectangle is the target area of research.

2.1 Tectonic Evolution

Cenozoic tectonic evolution was controlled by three major factors, which are; the spreading of South China Sea, the strike-slipping of Red River Fault zone, and the compression of Philippine plate (Fig. 1a), and went through three major tectonic evolution stages, including the multi-episode rifting stage, the regional thermal subsidence stage, and the neo-tectonic stage since late Miocene. According to Ru, K. and J. D. Pigott 1986 and (Sun, Zhong et al. 2009), the SCS region has undergone three major rifting episode with north to south trending extension along the northern continental margin (Cullen, Reemst et al. 2010). In the PRMB, extension regime started in the Late Paleocene (~ 59 Ma) as estimated by (Sun, Zhong et al. 2009)

and Franke (2013) and ended in the late Oligocene (Clift and Lin, 2001).

2.1.1 Break-up

The Paleogene epoch saw the failing of some rift basins while few others tore up to generate oceanic crust and mid-oceanic spreading center. Earlier studies of magnetic anomalies in the SCS central basin indicated that seafloor spreading began at around 30Ma, anomaly C11 (P. Wang and Q. Li., 2001). Revised time scale of Cande and Kent (1995) (Taylor, B. and D. E. Hayes 1983; Brais et al., 1993; Barckhausen and Roeser, 2004) from the oldest magmatic anomaly put the initial break-up age of SCS at ca. 29-31 (M.B.W. Fyhn et al 2009). The south China Continental break-up was a non-synchronous (Barckhausen, U., et al. (2014). The spreading began at the eastern half of the paleo-South China margin at around 33-32 Ma, while the western portion of the continental shelf remain in a less intense extension phase until 28-27Ma or 23.8 due to continuous rifting Zhou, D., et al. 1995 and Barckhausen, U., et al. 2014.

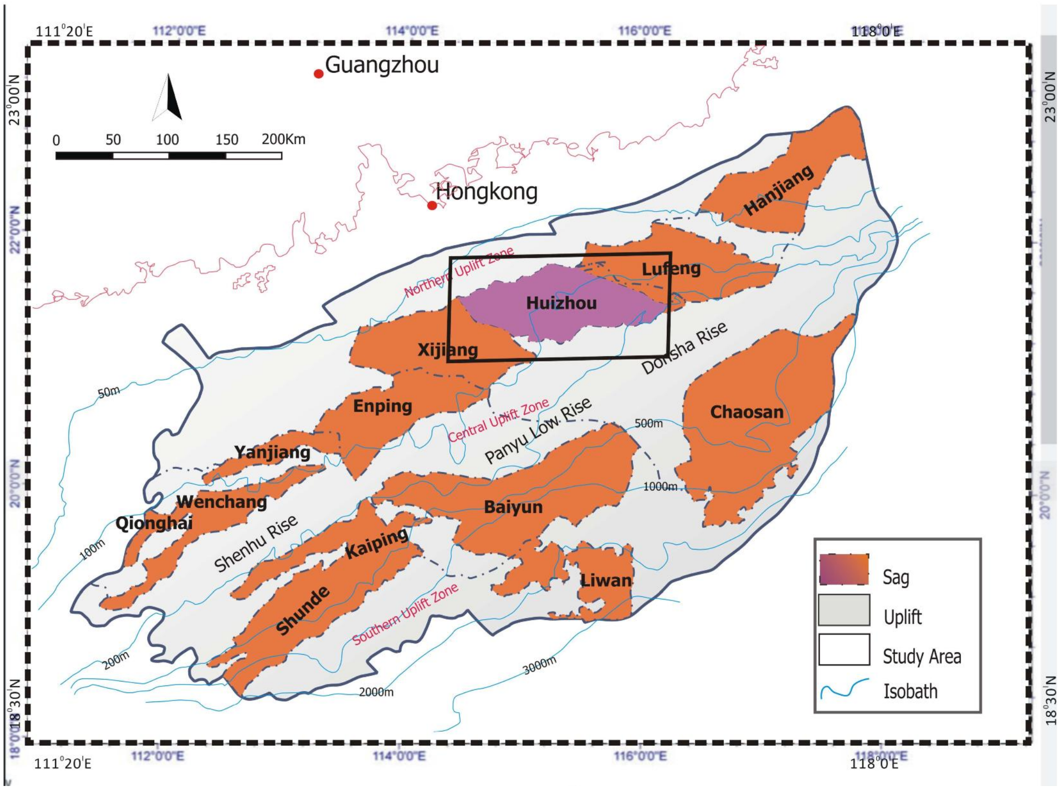

Fig.3 Map showing sags distribution in PRMB. Huizhou sag indicated in Purple.

2.1.2 Sedimentation and Stratigraphy

Non-marine fluvial and lacustrine sedimentation dominated the shelf basins in pre- and syn-rifting periods. Transition to marine sedimentation varies from late Oligocene-earliest Miocene in the north. The PRMB Fig.1b received sediments mainly from the Pearl River. Sediment infills consist of generally continental Paleogene and marine Neogene sediment deposits. Studies have shown that SCS area experienced both rifting and post-rifting stages divided by a breakup unconformity (Chen et al., 2003; Gong and Li, 1997; Zhou, D., et al. 1995; Ru, K. and J. D. Pigott 1986). The breakup unconformity is diachronous in age, aging in west-east direction (Zhou, D., et al. 1995).

The stratigraphic section of Huizhou sag (Fig.3) can be divided into 7 depositional sequences based on both well and seismic sequencing. From the base, Wenchang and Enping are regarded as syn-rift deposits of Paleogene and are dominated by continental lacustrine deposits while Zhuhai, Zhujiang, Hanjiang and Yuehai of late Paleogene-Neogene are post rift marginal marine and fluvial deposits that show increasing marine influence towards the shallower depth.

2.1.3 Thermal subsidence

Crustal stretching during rifting accounts for basin tectonic subsidence while further subsidence is experienced during the post-rift thermal cooling phase. Unlike in the rifting episode which results into restricted depressions, thermally controlled subsidence exhibits broad subsidence which involves and connect the different isolated depressions in a basin forming unified large depressions. The northern belt (Fig. 2) corresponds roughly to the Zhu-1 and Zhu-3 depressions in the northern PRMB; the middle belt to the eastern Zhu-2 depression of PRMB. The southern belt which extend from the Central Depression of QDNB eastwards, through the North Xisha Trough, to the continental slope north of the major portion of the SCS deep-sea basin were all fairly connected connected due to regional thermal subsidence. The distribution of these three belts of thermal subsidence shows only minor inheritance of the three belts of rifting indicating that thermal subsidence was mainly controlled by the extend of crustal thinning. Zhou, D., et al. 1995.

3 Data and methods

2D seismic reflection data and log data of Huizhou sag provided by China National Offshore Oil Corporation (CNOOC) were used for this study. Stratigraphic age control is derived from drilled sites in the Huizhou oilfield; HZ21-1-1, HZ25-3-2 and HZ28-1-1. Age control is based on nannofossil biostratigraphy for drilling sites in the PRMB. The following ages were tagged with their respective horizons; 32 Ma (T70), 23.8 Ma (T60), 18.5 Ma (T50), 16.5 Ma (T40) and 5.5 Ma (T30). The youngest age 2.23 Ma (T20) is inferred from the study of Li et al. (2009). Applying simple seismic interpretation principles, seismic sequences that reflect the structure and stratigraphic development of the study area were developed from depositional strata.

4 Interpretations and Discussion

From Fig. 4 (top) above, seismic section profile of southern Huizhou sag was analyzed by fault picking and horizons interpretation. The sag is wide in lateral distribution and in plane shape of rhombus and square approximately, with small formation dip in sag which becomes bigger near to the faults controlling sags visible from reflector geometries of uninterpreted seismic section. Firstly, fault were picked and based on the control of main faults (Fig. 4 bottom), the depression can be divided into two sub-sags, one controlled by double faults (SE Margin) and the other controlled by single fault (NW Margin). At the basin scale, Huizhou sag disposed of many multidirectional faults (NE-NEE, EW and NWW) controlling sags which were strongly active in fault period before the break-up (T70) and formed larger sedimentary thickness like the Wenchang Formation (Fig. 4 bottom). The faults are generally high angle normal faults which extended from the upper crustal rock and cut through most of the basin strata. i.e Fig. 4 bottom.

Secondly, horizons were interpreted and eight seismic sequences boundaries were mapped from Seabed to TB (Fig. 4 bottom) and where available, their corresponding age assigned based nannofossil biostratigraphy provide by CNOOC for drilling sites in the PRMB. Where no log data was available, i.e T80 and TB basic seismic stratigraphic principles was applied to achieve the best fit, therefor, I placed the TG roughly at the base of Wenchang Formation (49 Ma), along a set of strong distinct reflectors representing clastics sediment in a lake and T80 at the top of Wenchang Formation (39 Ma) along a set of long, continous reflector marking a surface of unconformity, Fig. 4 bottom.

From observation, Fig. 4 bottom, has a double layered geometry (Zhou, D., et al. 1995); the rifting phase, which is graphically represented by the wedged-shaped strata bounded between the surfaces TB-T40 and the post-rift phase represented by the blanket shape strata interfaced T40-Seabed. The rifting phase is characterized by tilted sedimentary layers dissected by faults with significant truncation at the T40 interface. This rifting phase, unlike the northern part of Huizhou or the rest of the northern margin where rift terminal is mostly at T70 or between T70-T60 where there is significant offset, identifiable by truncation marking the breakup unconformity, a short but sharp period of uplift of the rift flanks and typically truncates the wedge-shaped syn-rift sediments in the rift basins. Franke, D. (2013). Here, the rift truncation is observed at T40 interface.

Post-rift strata appeared relatively thin, continuous, less tilted and visibly unfaulted. Represented by interface T40, T30 and T30 date from 16.5-2.23 Ma they draped over the rifted topography and represent the thermal subsidence phase.

From interpretation, (Fig. 4 bottom), fault activity continued strongly after the break-up unconformity (T70) as evidence from the strata offset across the studied basin. The cessation of rifting from interpretation is therefore put at T40, (16.5 Ma) where significant truncation and inception of the post-rift drape strata were observed. Above the T40 interface, no clear large-scale faulting was observed similar to post-rift features in the northern part of the basin and other basins across PRMB. This Mid-Miocene fault activity is a clear case of "rifting cycle" comprising active rifting and its subsequent cooling phase (Chen L., 2014) and is not the same as the renew extension in Late-Miocene observed by Xie, X., et al. 2006 or the Mid-Late Miocene neotectonic extension which post-date both the primary rifting and thermal subsidence, documented by Angelier et al., 1990; Briais et al., 1993; Lin et al., 2003; and Tensi et al., 2006. It also evidently lack through going fault dissecting the post-rift strata.

It contradicts the view that no extensional features marked by localized normal faults exist on the proximal margin of the Northern passive margin. Savva, D., et al. (2013) and this Mid-Miocene (16.5) tectonic extension cessation does not fairly match the concept of syn-rifting to post-rifting basin development along the shelf margin of northern SCS (Zhou Di et al 2009). Huizhou sag and other basins in PRMB were said to become tectonically quiescent since 32-23.8 Ma, Clift and Lin 2001. Other studies of western part of northern passive margin basins (Zhu, W. and C. Lei 2013) have also documented that no clear large-scale faulting observed after the break up 32 Ma.

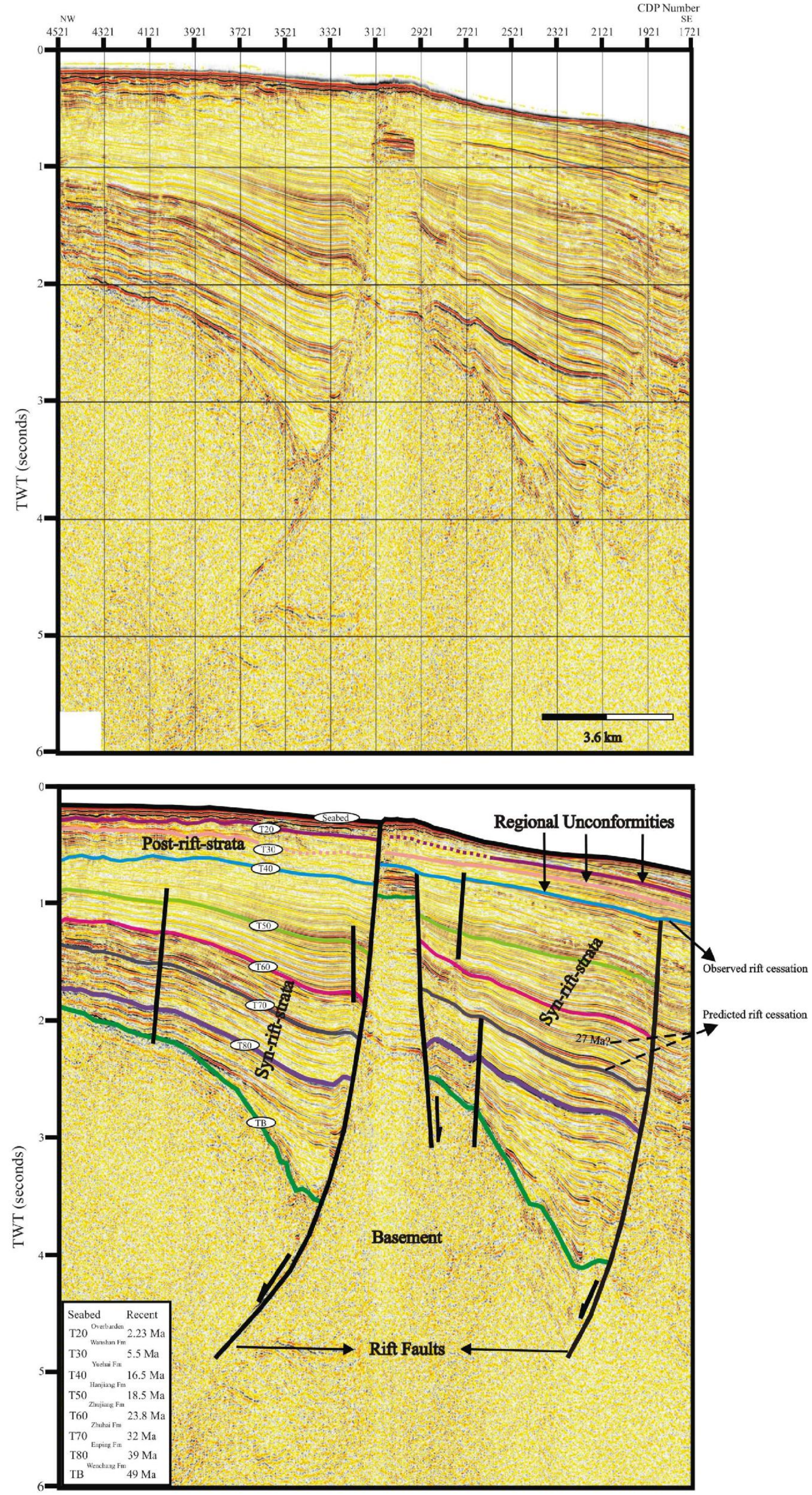

Fig.4. (top) Prestack time-migrated seismic reflection image and (bottom) interpretation along the Profile (see Figure 2).Large strata offset are imaged at the northwest and Southeast of the rift basin, seperated by a faulted crustal block.

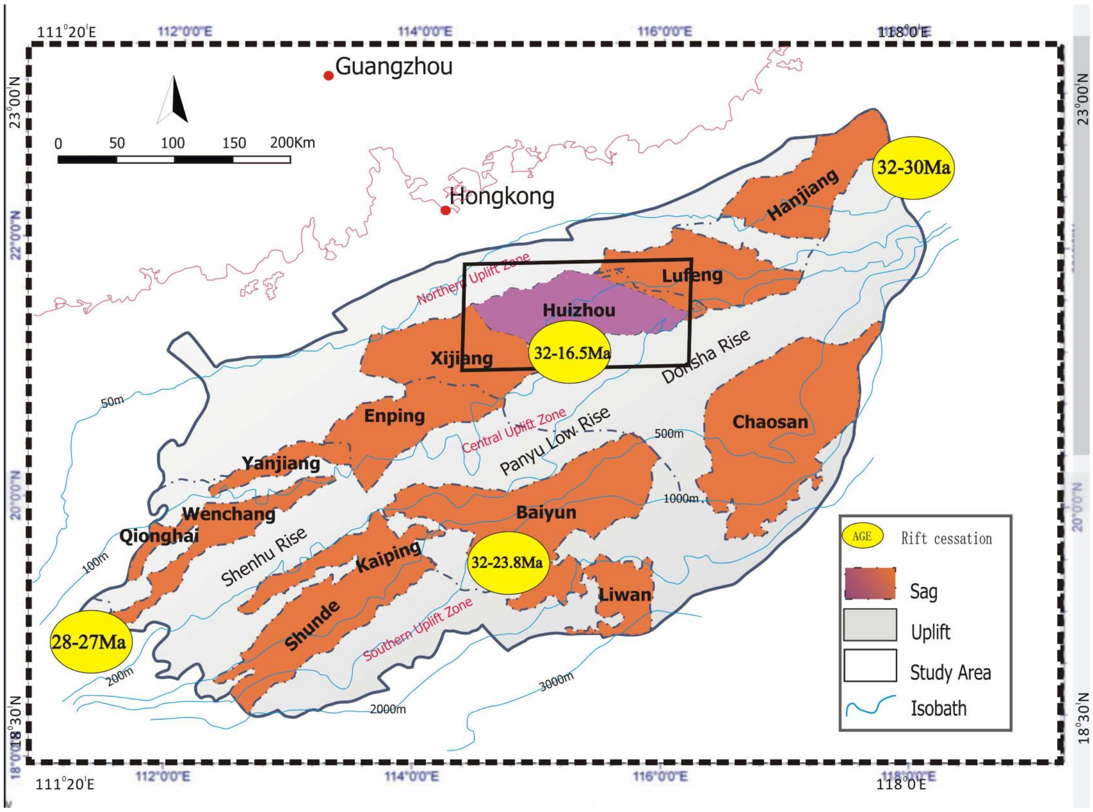

Fig.5 showing the compiled approximated age of rifting cessation across the Pearl River Mouth Basin with significant diachronicity observed across the basin edges. The ages are based on the termination of active crustal extension observed across PRMB by Zhou et al. (1994), Clift and Lin. (2001), Franke, D. (2013), Savva, D., et al. (2013) and this study.

This interpretation is non unique but the result is non-customary in the northern belt of NMSCS. However, similar renew fault activity has be documented along taiwan margin East of NMSCS (Angelier, J.,F. et al., 1990; Lin et al., 2003, Lester, R., et al. (2012) but no such major fault activity is recorded in the west of NSM. (Yin, X et al, (2011).

The observed post break-up extension reflects a multi-phase extension within an individual basin (Allen & Allen., 2005) or preferential extension (Chen L., 2014) as it was only observed south of the study basin. These significant age variation in the post-break-up fault activity and the post-rift thermal phase offset within the basin can (1) impact the basin geometry, (2) also affect the conventional basin subsidence parametization as mentioned by Chen L., 2014 (3) may result in disproportionality in basin subsidence mechanism partitioning between the crust and lithosphere. (Westaway, R. 1994. Yin et al. (2011); Zhu, W. and C. Lei 2013). And (4) also can result in underestimation or overestimation of subsidence, as subsidence in the rifting stage is a function of stretch factor β and rift duration. The post-rifting subsidence decreased exponentially according to the law of thermal contraction during lithosphere cooling (Jarvis and McKenzie, 1980; McKenzie, 1978)

Consequently, from this study, rift cessation across PRMB is not everywhere the same as earlier reported by (Clift and Lin 2001). Variation in age of rift termination across PRMB is 33 to 32 Ma in the eastern, and from 28 to 27 Ma in the West, 23.8 Ma south of Central region and 16.5 Ma (this study), north of central region. Figure 5. This localized fault activity add complexity to the basin evolution history across SCS and similar work need to be carried out in other basins to accurately date the fractures and re-estimate crustal extension Savva et al. (2013).

Conclusions

The 2D seismic refection data and well data provided a new age constraints for rift cessation in the shelf region of PRMB. Through critical interpretation, re-evaluation of rift activity of extensional normal fault terminating at the upper crust, and review of existing literature, new age is added to the rifting cessations already documented for the northern shelf margin of SCS. The data provided evidence for a younger age (16.5 Ma) of rift cessation in the shelf region of PRMB, northern SCS contrary to the collective age 23.8 Ma proposed by earlier research. The intension is not to challenge the record but rather to present a diachronity in age of rift activity in the central belt of PRMB.

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