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# Polyphase rifting of greater Pearl River Delta region (South China): Evidence for possible rapid changes in regional stress configuration

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ABSTRACT

The greater Pearl River Delta (PRD) Region, consisting of several late Mesozoic–Cenozoic basins, has preserved information on the tectonic history of the coastal region of South China. An integrated morphological and structural study of the basins has revealed several phases of extension subsequent to the collapse of the Mesozoic arc magmatism. A N–S extension associated with the exhumation of the magmatic arc during the late Mesozoic–early Cenozoic was followed by an ENE–WSW extension producing NW-striking normal faults in the region. Paleo-stress analysis of fault slips measured at seven localities reveals stress configurations consistent with the field observation. The basin development during the Cenozoic was strongly controlled by relative motion of neighboring plates as well as pre-existing structures. The results suggest that stress configuration can change relatively rapidly in a continental margin undergoing a transition from an active-margin to passive-margin.



## 1. Introduction

The coastal province of South China represents a continental margin that underwent a transition from an active-margin to a passive-margin during the Late Cretaceous–early Cenozoic time. The region is characterized by an extensive Mesozoic magmatic belt and prominent NE-striking fault zones developed during the northward subduction of a paleo-Kula-Pacific plate beneath South China (Mark and Geoffrey, 1982). Extensive exhumation of plutons occurred during the active to passive continental margin transition (Hsü et al., 1990; Lapierre et al., 1997). The rifting probably commenced during as early as the Late Cretaceous, producing faulted basins both onshore and in the continental shelf (Faure et al., 1996; Zhou and Li, 2000; Zhu et al., 2004). The offshore basins, including the Zhujiang and the Qiongdongnan Basins, are elongated in a generally E–W direction and were formed mainly during the late Eocene–Oligocene (Li and Rao, 1994; Zhou et al., 1995; Ludmann and Wong, 1999; Ren et al., 2002). The tectonic origin of the terrestrial basins in the onshore region is not well understood. Zhu et al. (2004) regarded them as pull-apart basins while Zhou et al. (1995) suggested that they were formed by simple rifting along two adjoining faults. A better understanding of the nature of the basins is therefore critically important for the reconstruction of the tectonic history of South China during the continental margin transition.

In the study described in this paper, we carried out detailed structural measurements at selected localities in the greater Pearl River Delta area in an attempt to unravel the tectonic deformation history of South China during the continental margin transition. Topographic features and drainage characteristics were delineated using satellite images and Shuttle Radar Topography Mission (SRTM) data. Field measurements of geological structures and a paleo-stress analysis were carried out to delineate the post-orogenic extension history of the study area.

## 2. Morphotectonic and structural setting of the greater Pearl River Delta region

The study area, located between longitudes 111°30′E and 115°E and latitudes 21°40′N and 24°N, is part of the greater Pearl River Delta region in South China (Fig. 1). The region consists of a series of NE–SW striking fault zones intersected by less prominent NW–SE striking faults (Fig. 1). The two sets of faults dissect the entire region into a checkerboard-like pattern. The cross-cutting relationship between the two sets of faults is obscure, but present-day seismicity shows that both sets of faults are apparently active. Geophysical data compiled by LDAC (1989), Zeng et al. (1997), Wei

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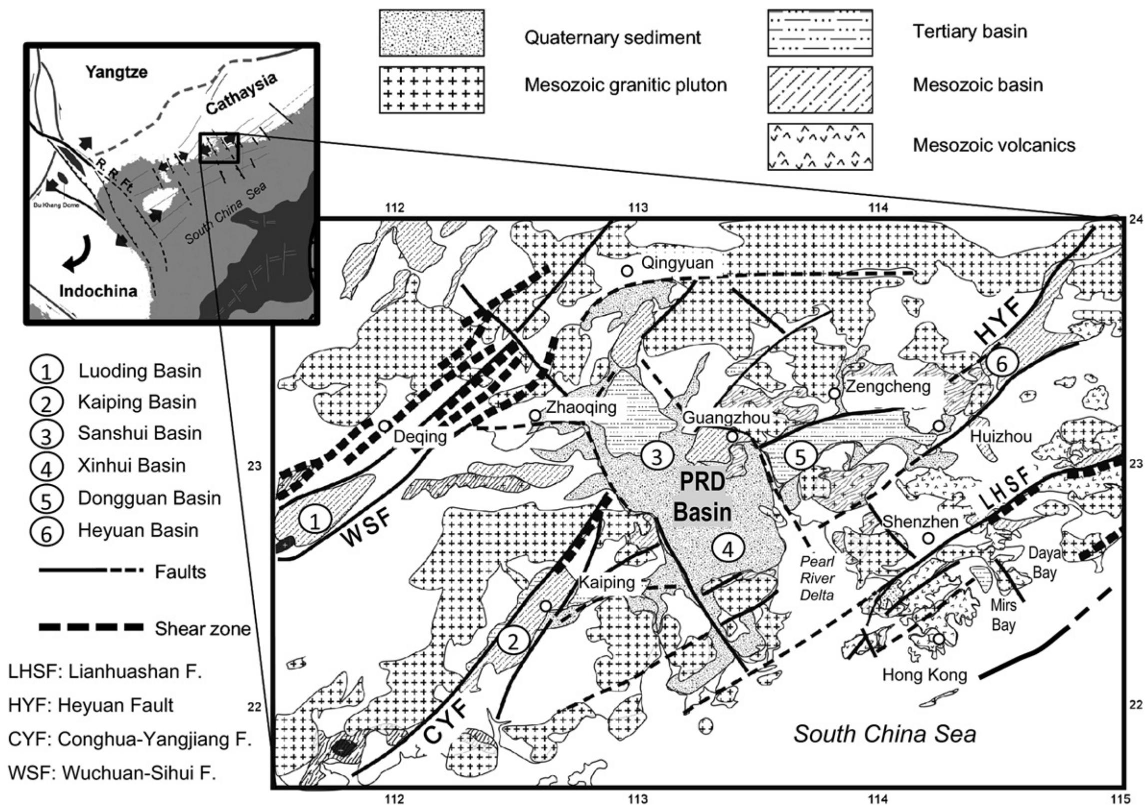


**Fig. 1.** Simplified geology of the greater Pearl River Delta (PRD) region, based on Bureau of Geology and Mineral Resources of Guangdong Province (1988).

(2001) and Pubellier and Chan (2006) reveal a gradual thinning of the crust towards the southeasterly direction and an E–W directed principal stress in the present day (Fig. 2). The major NE-striking fault zones, including the Wuchuan-Sihui Fault (WSF), the Conghua-Yangjiang Fault (CYF), the Heyuan Fault (HYF) and the Lianhuashan Fault (LHSF), developed along older ductile shear zones and were probably reactivated during the exhumation of the basement (Sewell et al., 2000; Fletcher et al., 2004).

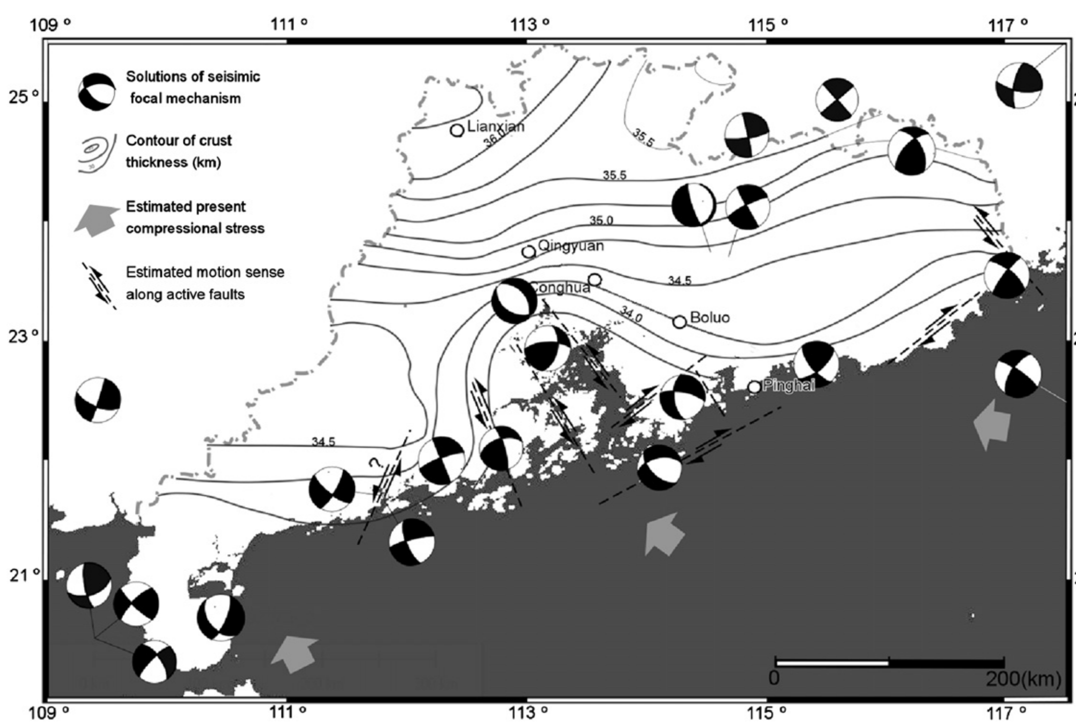


**Fig. 2.** Estimated crustal thickness, focal plane mechanism and present-day principal stress directions of Guangdong area based on Zeng et al. (1997), Wei (2001) and Pubellier and Chan (2006).

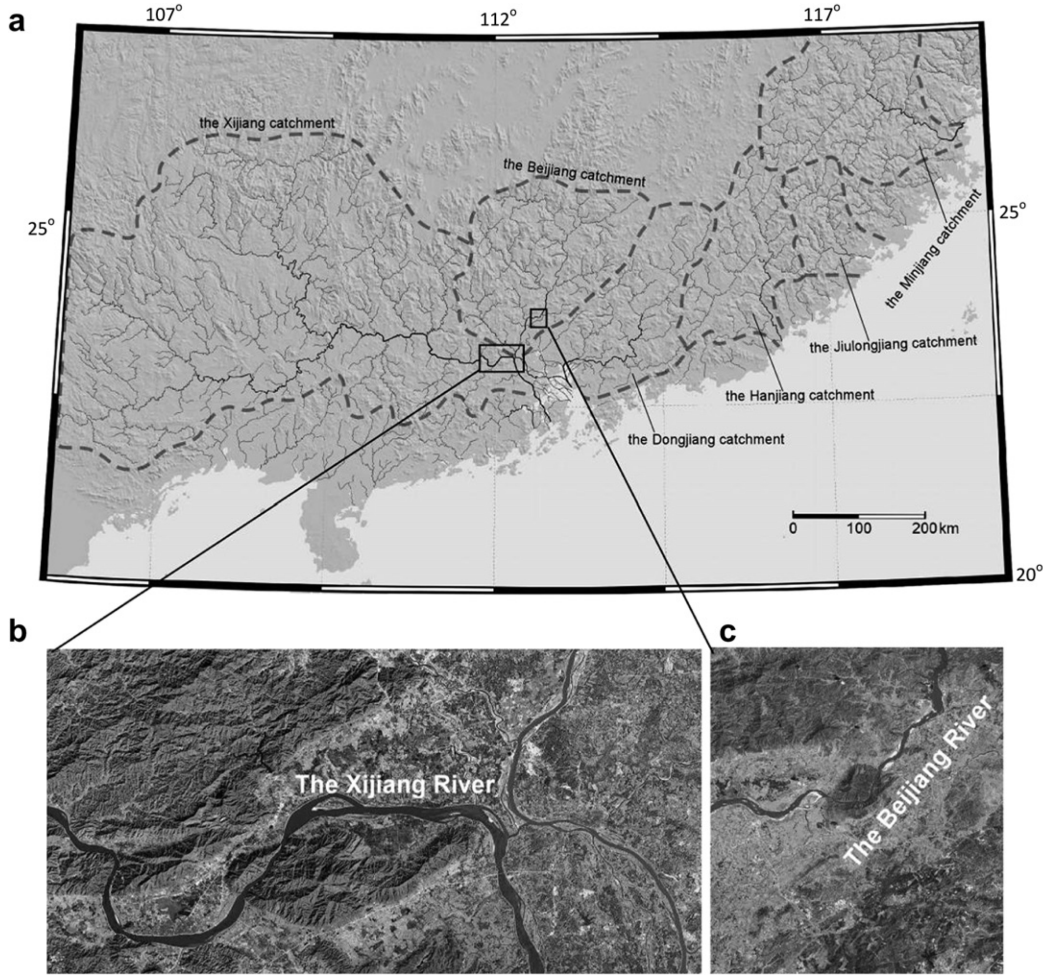


**Fig. 3.** Drainage anomalies in the PRD region and surrounding areas. (a) Drainage network in the coastal region of South China; (b) Xijiang river which follows an east–west striking fault and makes an abrupt turn towards the SSE; (c) Antecedent drainage of the Beijiang river indicates control of the drainage by E–W structures.

The area contains some of the largest and Cenozoic-age terrestrial basins in South China, including the late Mesozoic-age Kaiping Basin and the Cenozoic-age Dongguan, Sanshui and Pearl River Delta (PRD) Basins. The sediments within the Mesozoic basins are generally tilted and occasionally folded, while the sediments in the Cenozoic basins are mostly sub-horizontal. The PRD Basin marks a rectangle-shaped depression extending from the coast northwestwards for more than 100 km into the magmatic arc. Its age is controversial; Zhou et al. (1995) suggested that a proto-PRD basin was formed during the late Mesozoic–early Cenozoic either as pull-apart or a back-arc basin, while Huang et al. (1982) and Wei (2001) regarded it as a Quaternary graben.

Three major drainage systems, namely the Xijiang (Western River), Beijiang (Northern River) and Dongjiang (Eastern River), are present within the study area (Fig. 3). A strong structural control on the development of the drainage systems is evident. Both the Xijiang and Dongjiang rivers follow an E–W course along latitude 23.2°N for a combined distance of over 500 km. West of the PRD Basin, the eastward flowing Xijiang river cuts through over 1 km of Devonian formations in an anticline and takes an abrupt turn towards the SSE into the PRD Basin near Sanshui. The Dongjiang River follows a westerly course and turns similarly towards the SSE near Guangzhou. The three rivers join to form the Pearl River Delta System, which is characterized by a series of subparallel and linear distributaries trending in a NNW–SSE direction. The ability of the distributaries to maintain very linear courses despite the lack of relief is indicative of the strong control of the river development by neotectonic motions involving basement structures.

## 3. Structural measurements and paleo-stress inversion

The presence of multiple post-orogenic extensional episodes is evident in the greater PRD region. Detailed structural measurements were conducted at ten localities within area; the localities are grouped into five areas based on their geographic locations. Bedding attitude and kinematic indicators such as drag fold, tension gashes, schistosity, C-S fabrics, Riedel shears, fault-plane orientation, and fault-slip were studied and measured. The multiple inverse method developed by Yamaji (2000) and subsequently modified by Yamaji (2003) was applied on the fault-slip data to delineate phases of kinematic movement and the associated stress tensors for the localities. The inversion necessarily assumes a linear and isotropic plasticity of the rock mass, and the slip vectors occur in the direction of the maximum shear stress on the slip surface. Fault-slip data are grouped into subsets using a recursive procedure, and the optimum stress tensor is calculated for each subset of fault slips by minimizing the angular misfits between the predicted and the measured fault-slip values. A good clustering of stress solutions thus represents a persistent stress field, and the number of solution clusters indicates the number of tectonic episodes experienced by the rock mass.

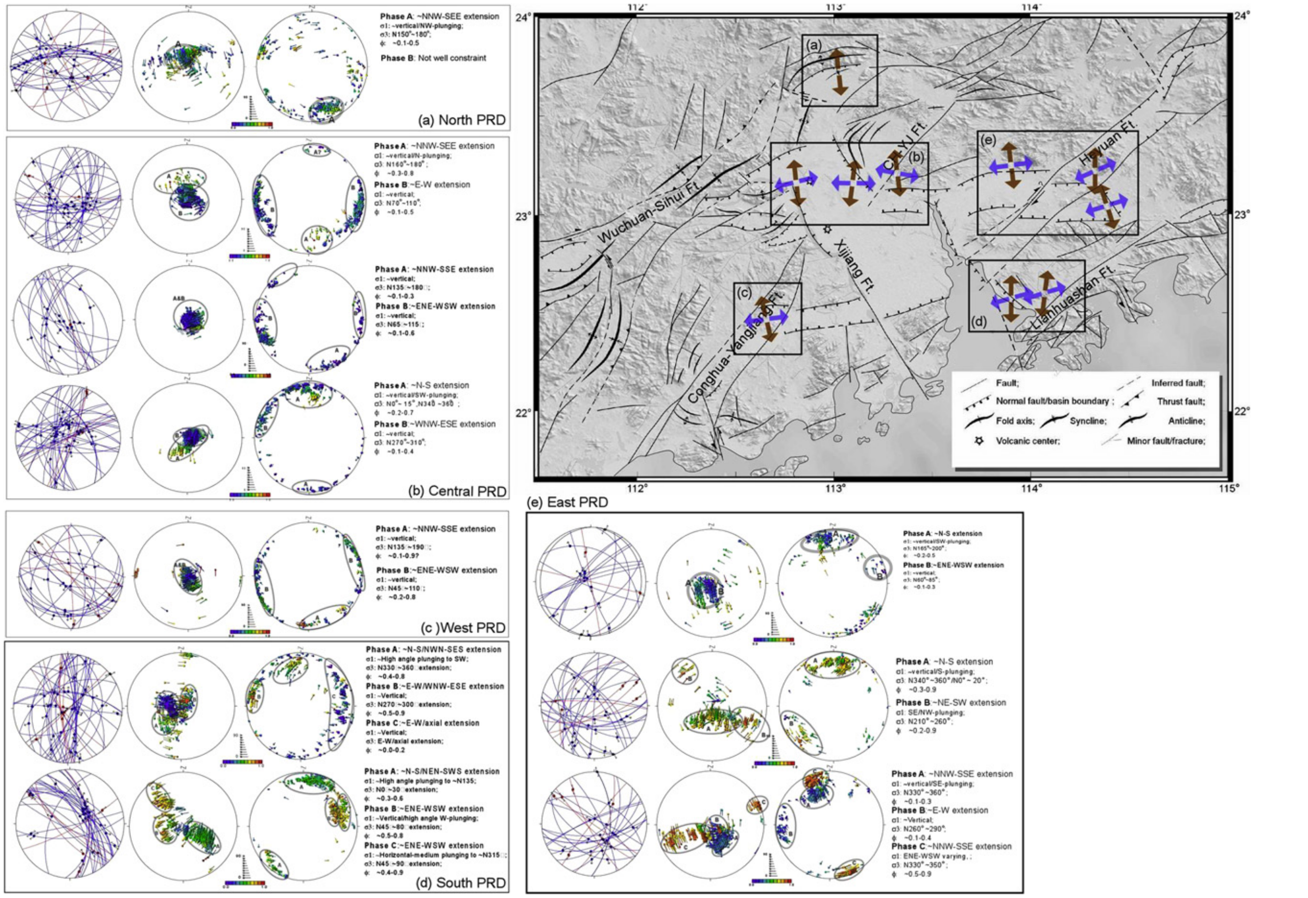


**Fig. 4.** Fault-slip data and paleo-stress inversion in the greater Pearl River Delta region using the multi-inversion method. Two phases of extension are evident in the stress tensors obtained from the inversion.

In the field, the fault-slip vectors were either determined from slickensides on the fault planes or inferred from secondary structures such as tension gashes, Riedel shears and P-shears. For the Riedel shears and P-shears, the direction on the fault surface normal to the line of intersection between the fault plane and the shears was used as the slip vector. For tilted layers, the fault-slip data were corrected for the bedding attitude before the inversion was applied. A sub-group size of 8 was used in the inversion to estimate the principal stress directions and the stress ratios for each of the solution clusters. The paleo-stress inversion reveals the dominance of normal faulting events in all of the five areas (Fig. 4).

### 3.1. Eastern PRD area

The Dongguan Basin located east of the PRDB (Fig. 1) contains a series of late Mesozoic-age red beds dipping at 10°–70° to the southeast. Paleo-stress solutions obtained for the area reveal two extensional phases, one in a N–S to NNW–SSE direction and another in an ENE–WSW direction (Fig. 4, East PRD). One of the datasets shows a primarily NE–SW compression. Near Huizhou, a set of faults striking at N60°E shows a post-Mesozoic extension in a NW–SE direction (Fig. 5a). Tilted conjugate sets of normal fault indicate a subsequent phase of extension in a generally NE–SW direction (Fig. 5b). Tension gashes present on the NE-striking faults are also indicative of a general NNW–SSE extension; the faults are cut by secondary N–S striking faults and fractures, indicating a second phase of extension in an approximately E–W direction. Some of the NE-striking normal faults also show a later phase of reverse motion. In a granite quarry near Zhengcheng, a sub-horizontal shear zone consisting of mylonite, gneiss and migmatite displays a prominent schistosity dipping at about 30° towards the SE, and tension gashes and normal faults striking in an E–W direction. The shearing was probably associated with the exhumation of granite in a N–S direction. A second phase of extension is represented by a 2 m-wide felsic dyke striking NW. Structural relations observed at Huizhou and Zhengcheng indicate a younger age for the NE–SW extension relative to the NW–SE or N–S one.

### 3.2. Central PRD area

The fault-bounded Sanshui Basin covers an area of over 1500 km$^2$ and represents the largest terrestrial basin in the greater PRD area. The basin contains a thick sequence of Late Cretaceous–early Cenozoic continental deposits overlain by volcanogenic formations which have yielded a radiometric age of 38–56 Ma (Zhu et al., 2004). In the western part of the basin, a Quaternary conglomerate rests unconformably upon Paleocene-Eocene mudstone, suggesting an Eocene age for the youngest pre-Quaternary sedimentation in the basin. Extensional structures are commonly present in the sedimentary and volcanogenic rocks within the Sanshui Basin. The paleo-stress inversion of fault-slip data from the area reveals two phases of extension (Fig. 4, area Central PRD). The relation between the two extensions can be established from observed structures in the field. In the exposures shown in Fig. 6, a prominent N–S extension event is represented by well developed tension joints and normal faults, which were tilted in a later E–W extensional event. This extension continued

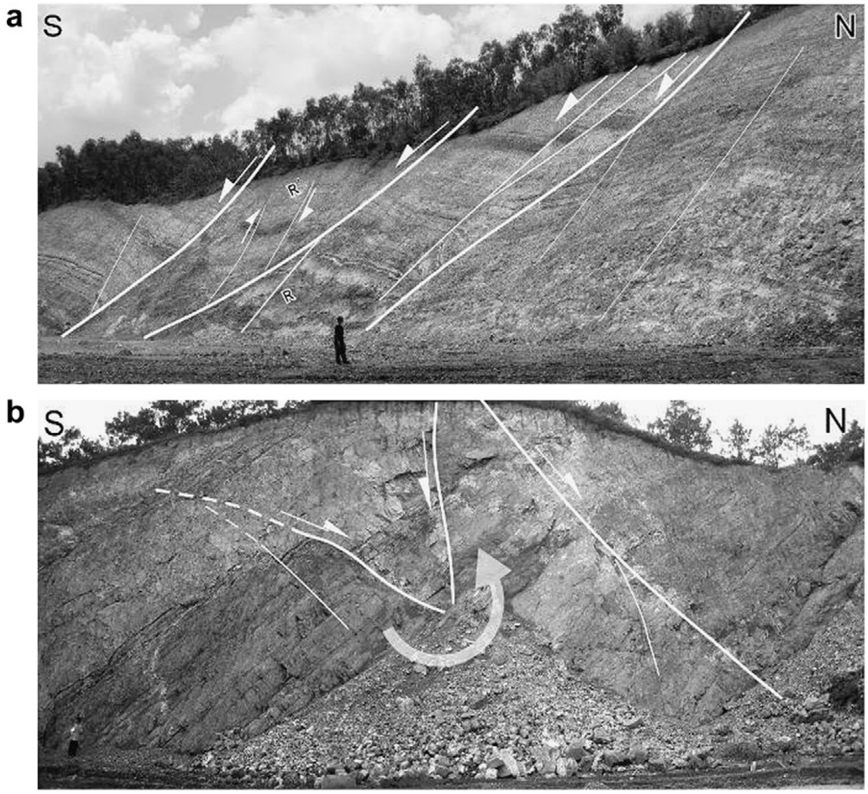


**Fig. 5.** Outcrops near Huizhou in Donggang Basin showing two phases of extension. (a) Normal faults in the Jurassic red beds showing an approximately N–S extension, with both synthetic and antithetic subsets; (b) Tilted conjugate normal faults in red beds showing two phases of extension.

at least into the late Eocene since the volcanogenic rocks were also affected.

### 3.3. Western PRD area

The fault-bounded Kaiping Basin, located west of the pearl River Delta Basin, is a Cretaceous red-bed basin extending for about 50-km in a northeasterly direction (Fig. 1). The Cretaceous clastic rocks in the Kaiping Basin are slightly deformed, with argillaceous rocks metamorphosed into a phyllite and the relatively competent conglomerate, sandstone and quartz veins stretched into boudins (Fig. 7). A strong S-C fabrics is observed along two sets of conjugate shear planes in the Cretaceous rocks. The S-planes are sub-horizontal; two sets of C-cleavages were observed, with one dipping gently to the SSE and the other steeply to the NNW (Fig. 8). Fault-slip data collected at two locations reveal two phases of extension, one in an approximately N–S direction and the other in an NE–SW direction (Fig. 4, West PRD area). The N–S extension affected both the Lower and Upper Cretaceous groups in a ductile manner and the faults associated with the NE–SW extension cut across the ductile cleavages, revealing a younger age relative to the N–S extension.

### 3.4. Southern PRD area

Paleo-stress inversion of fault-slip measurements from the southern PRD area reveals two phases of extension and a phase of a compression in a NW–SE direction (Fig. 4, area South PRD). The older extension is manifested in ductile shear zones and low-angle normal faults in the Mesozoic granitic plutons in Hong Kong and Shenzhen. In the western part of Hong Kong, C-S fabrics in shear zones in a granitic pluton reveal extensions both in N–S and E–W directions. In the southern part of Shenzhen, a low-angle fault striking WNW–ESE is present with Carboniferous formations overlying the Jurassic tuff. Schistosity and cleavages in the tuff dip respectively at 30°–60° towards the NNW and to the NW. Normal faults dipping at about 60° towards the NNE in the sheared tuff show an N–S extension, probably during the final stage of exhumation along pre-existing faults of the Linhuashan Fault Zone. The region also contains a few terrestrial and coastal basins, including the Mirs Bay and Daya Bay basins east of Hong Kong, which were probably formed during an ENE–WSW extension. The former is bounded by NNE–SSE striking normal faults well exposed on the margins of the basins. In an exposure located on the western margin of Mirs Bay, low-angle, E–W oriented detachment faults in Late Cretaceous red-bed formations are cut by N–S striking normal faults (Fig. 9). The field observations indicate a ENE–WSW extension postdating the phase of ductile extension.

### 3.5. Northern PRD area

The PRD basin is bounded on the northwest by the Wuchuan-Sishui Fault which follows the curvature of a series of S-shaped folds developed in Paleozoic formations near the city of Qingyuan (Fig. 10). The Devonian formations in the area are dipping at about 45°–70° to the SSE and overlying unconformably on Cambrian formations. A regional exhumation of the Paleozoic folds and granites probably occurred in a major phase of N–S extension. Several normal faults striking northeast dissect the area into a series of fault blocks with a less prominent set of east–west striking normal faults cutting across the region. Paleo-stress inversion of fault-slip data from this area reveals a single phase of N–S extension in this region (Fig. 4, area North PRD).

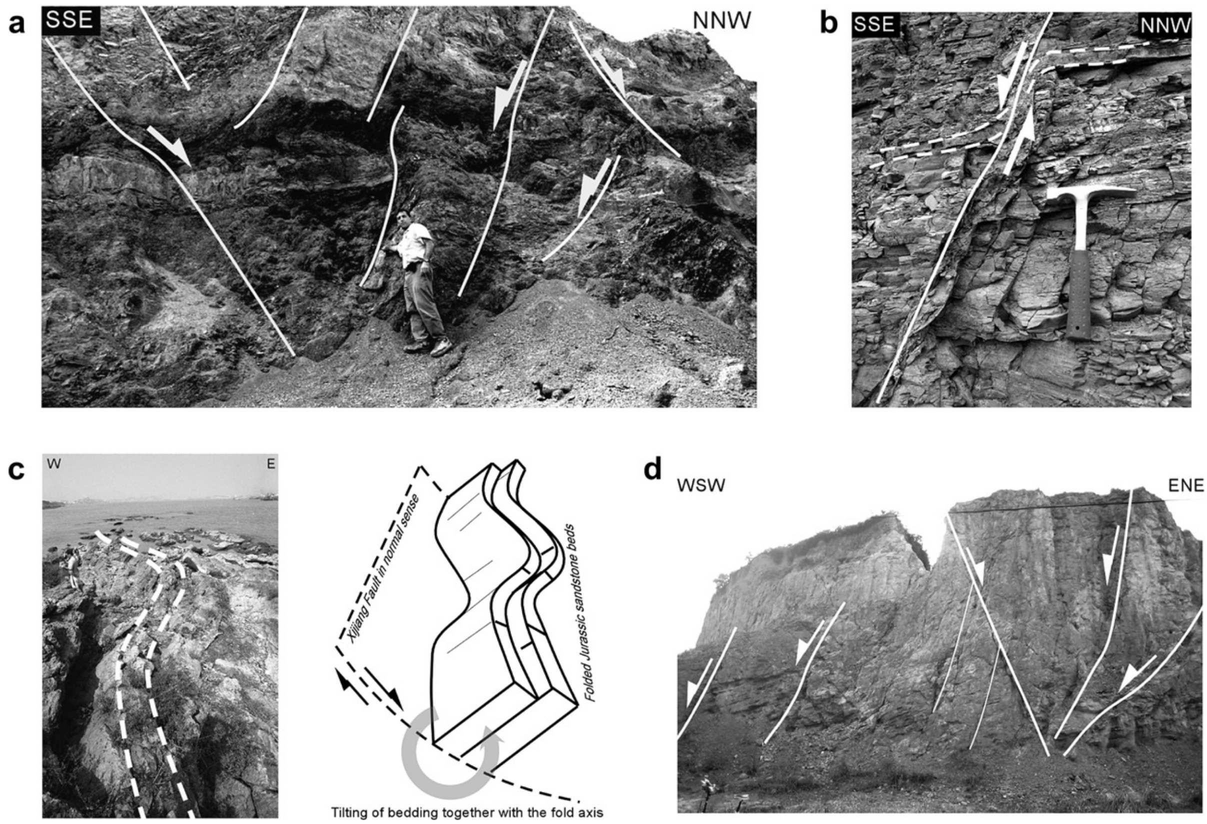


**Fig. 6.** Outcrops the central PRD region showing at least two extensional phases. (a) Conjugate syn-depositional normal faults developed within Eocene-age sandstone; (b) Drag folds in sandstone reveals a NNW–SSE extension; (c) Folded Jurassic rocks became tilted in a subsequent E–W directed extension; (d) Conjugate fault sets in Cretaceous rocks reveal a ENE–WSW extension. (a) and (b) are related to the N–S rifting phase; (c) and (d) represent structures formed during the E–W rifting phase.

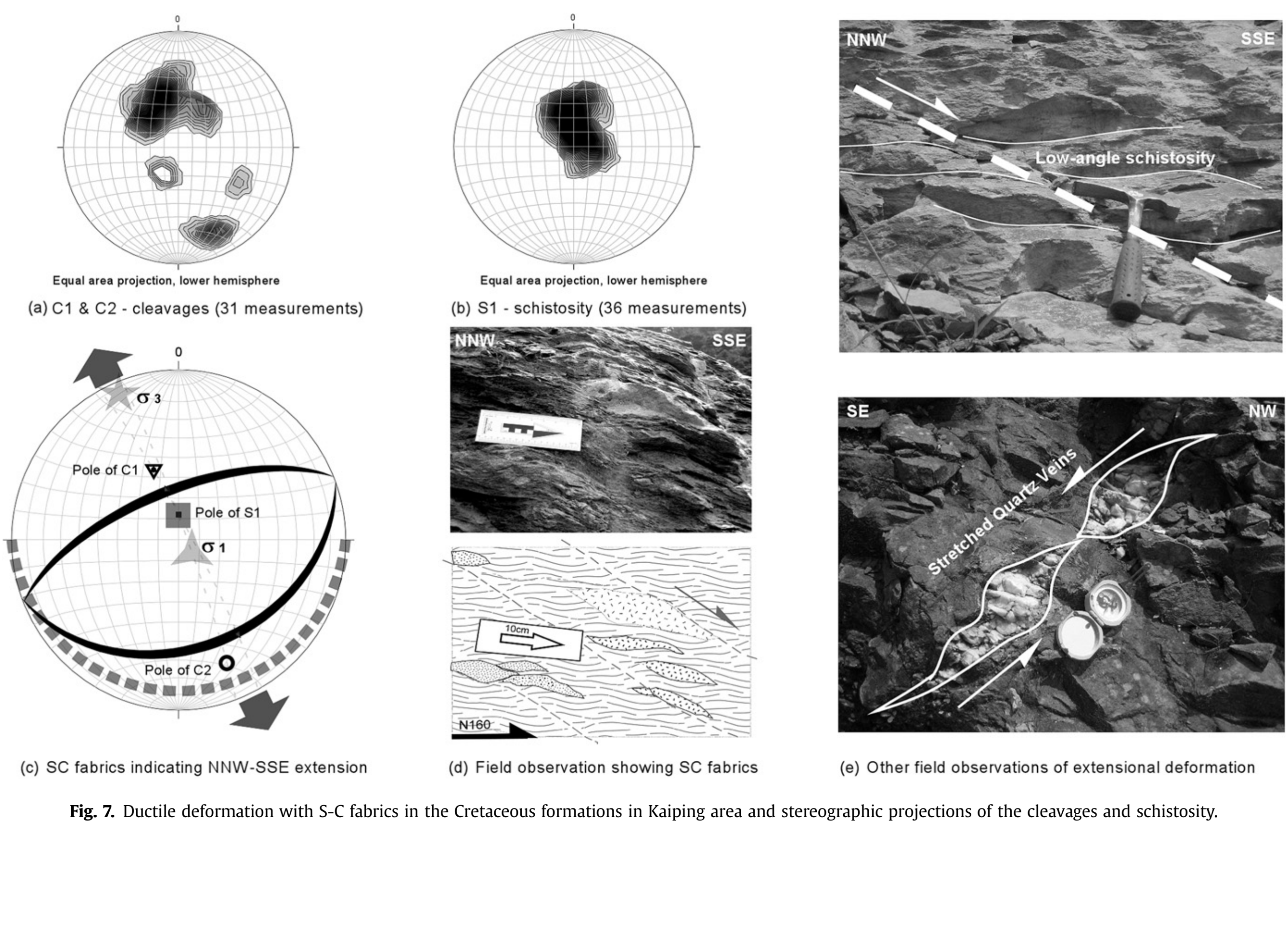


**Fig. 7.** Ductile deformation with S-C fabrics in the Cretaceous formations in Kaiping area and stereographic projections of the cleavages and schistosity.

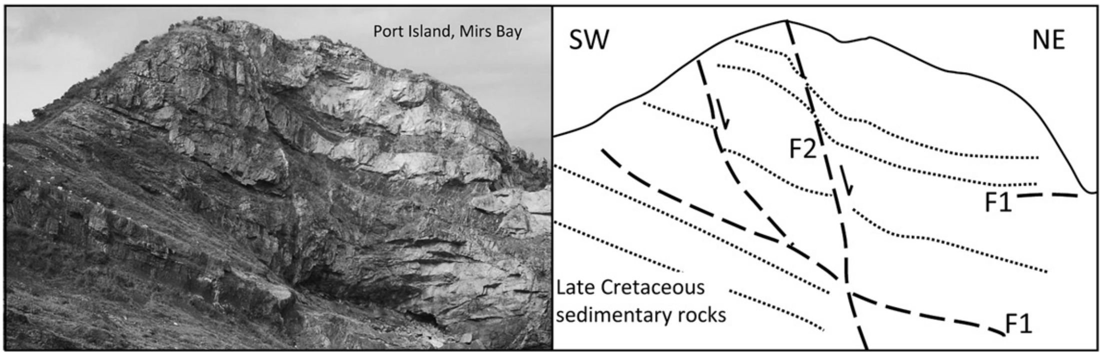


**Fig. 8.** Normal fault exposed on western margin of Mirs Bay. An older set of low-angle normal faults (F1) is cut by normal faults (F2) formed in a NE–SW extension.

## 4. Discussion

The present study of the Cenozoic structures reveals the dominance of extensional tectonics in the greater PRD region during the Late Cretaceous–Cenozoic time. Several phases of extension can be identified from the field study and paleo-stress inversion. The initiation of the extension was represented by the collapse of the Mesozoic magmatic arc leading to the formation of scattered terrestrial basins in the region (Fig. 10a). These basins were formed along pre-existing faults and did not acquire a particular geometry. This phase of crustal subsidence was soon followed by an extensive exhumation of the crust during the early Cenozoic (Fig. 10b). The rifting was mainly a "margin-perpendicular" extension and marked by NE–SW and N–S directed detachments and large normal faults. In areas where the faults were preserved in good condition, they clearly reactivated the short limb of the Yanshanian broad folds. The structures are partly buried by the second direction of rifting during the Neogene in the Pearl River Delta basin but are best delineated on satellite images.

The PRD basins are probably rifted basins developed on the attenuated margin of South China. The temporal relationship between the sediment age of the PRD basin and that of the offshore basins reveal a southward migration of the deposition centers. The oldest continental sediments in the offshore basins near the Pearl River Delta could be traced back to the Late Cretaceous (Zhou et al., 1995), indicating an initiation of the NE–SW extension shortly after the Mesozoic magmatic event. The deposition in the PRD basins ended in Eocene; the marine facies in the offshore basins did not develop until the late Oligocene (Cai, 2005). Field evidence and the inversion of fault-slip data have also revealed a prominent N–S extension in the region. This rifting reactivated older NE-trending shear zones as normal faults and caused river systems in the region to follow an E–W directed course (Fig. 10c). It is uncertain whether the N–S extension represents a distinctive phase of rifting or a gradual rotation of the extensional direction from a northwesterly to a north–south direction. In any case, the development of the terrestrial basins appeared to have ceased once the opening of the South China Sea was in full swing. A phase of 'margin-parallel' NE–SW extension is evident in the greater Pearl River Delta area.

While the initial development of terrestrial basins was controlled by pre-existing NE-striking faults, the N–S and NE–SW extensions are prominently manifested in minor normal faults within the terrestrial sediment in the basins. Wherever the two extensions are both evident in the same outcrop, the NE–SW

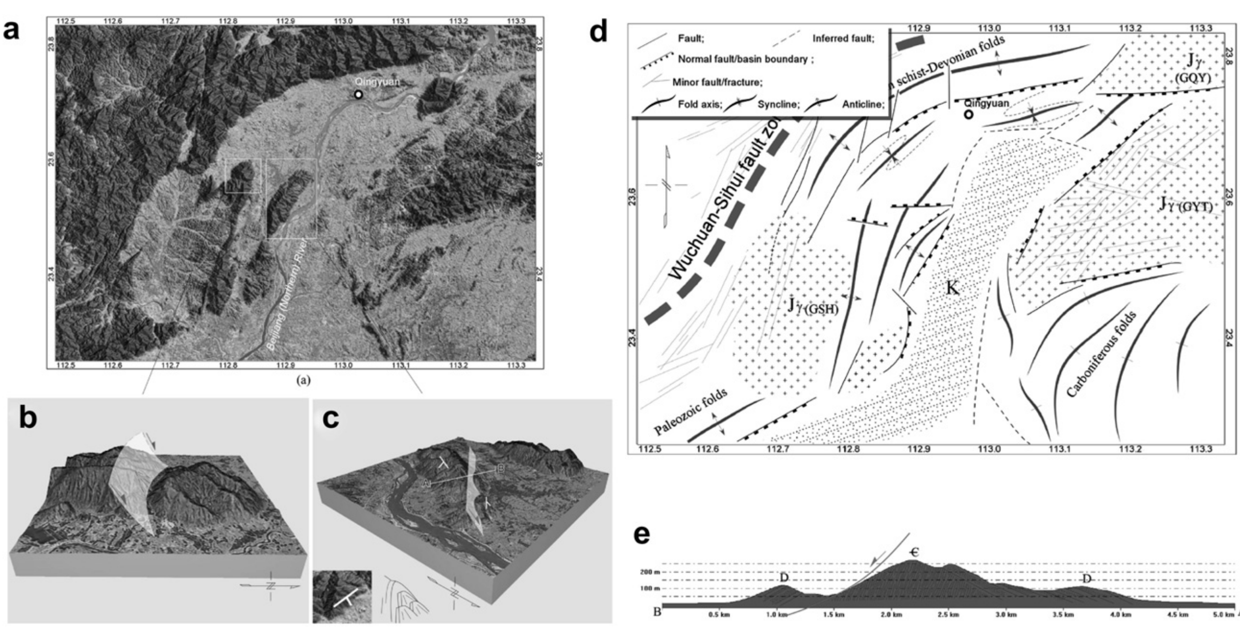


**Fig. 9.** Morphotectonics of the northern part of the Pearl River Delta area: (a) Satellite image of the Beijiang river and Qingyuan area; (b) Digital elevation model derived from SRTM data revealing presence of N–S extension; (c) A phase of extension detached overlying Devonian sandstone formations from Cambrian schist; (d) Structural analysis in the area showing the presence of a sigmoidal-shape red-bed basin; (e) Profile revealing a normal fault between the Cambrian and Devonian formations.

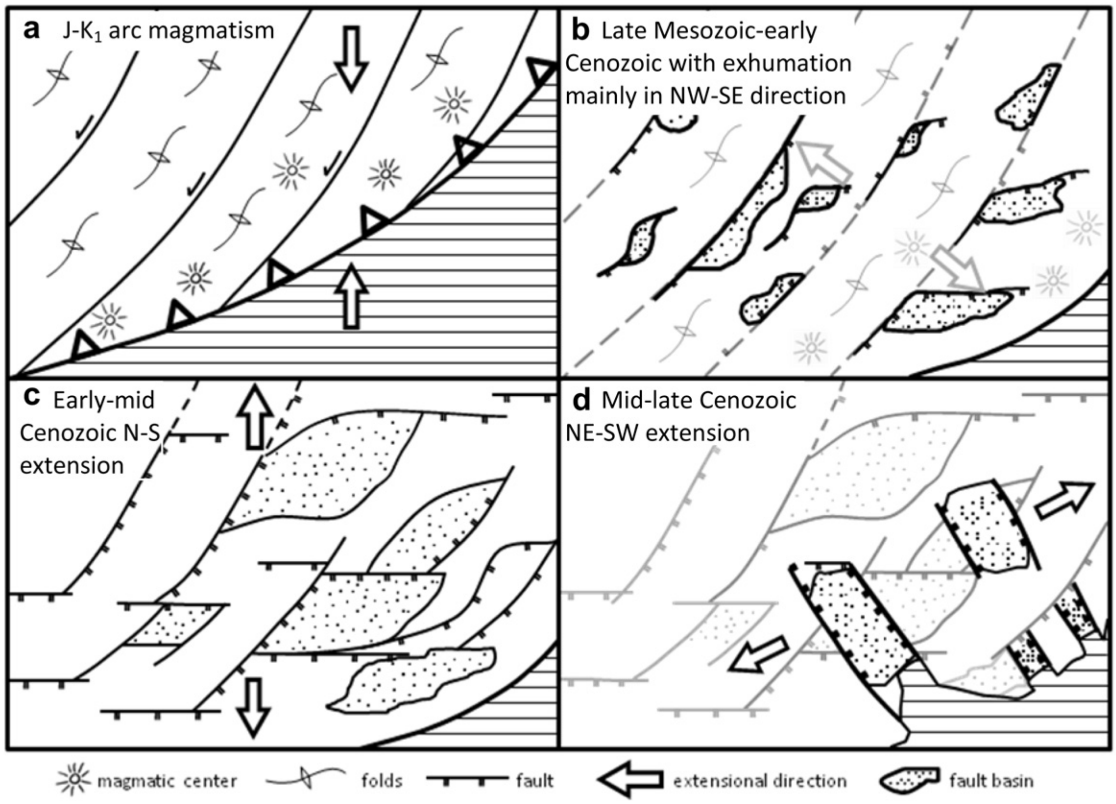


**Fig. 10.** Schematic model of tectonic evolution of Pearl River Delta region since the late Mesozoic: (a) Development of magmatic arc along convergent boundary; (b) Formation of subsidence basins and initial rifting mostly along NE–SW striking faults in NW–SE direction; (c) Crustal extension in N–S directions; and (d) Crustal extension in NE–SW direction.

extension appears to be the relatively younger one in most cases. The abrupt turn of the E–W directed Xijiang and Dongjiang Rivers to the southeast in the PRD Basin, the tilting of the Cretaceous red beds in Sanshui postdating the syn-rifting deformation in the Eocene sediments, and brittle faults associated with an N–W extension in Kaiping all suggested a younger age of the NE–SW extension relative to the NW–SE extension. In the Red River-North Vietnam area, the NE–SW extensional event was also found to cut the N–S one registered in many of the study localities (Pubellier and Chan, 2006; Pubellier et al., 2008). The tectonic nature of this NE–SW extension is unclear. The direction of extension is also contradictory to the current E–W directed principal stress in South China since the commencement of the collision between the Philippine Sea Plate and Eurasia Plate. A plausible explanation is that this extension represents a far-field effect of the tectonic activities along the Red-River fault zone. The studies by Yang and Besse (1993), Jolivet et al. (1999, 2001) and Schoenbohm et al. (2006) have shown that the exhumation of metamorphic core complexes in the Red-River area were associated with a NE–SW extension during the late Oligocene–early Miocene. The problem with this interpretation is that the exhumation in the Red-River area had already ceased during the late Miocene, but the Pearl River Delta Basin is still undergoing active subsidence.

The stress tensor inversion reveals a dominantly vertical σ1 at all of the study localities, arguing against a transtensional nature of the extensional phases. The minimum principal stress direction rapidly changed from a NW–SE to a N–S and to an ENE–WSW direction. Such a rapid change in stress configuration is not uncommon even in the modern seismicity of the region. An interesting implication is that the stress configuration of the region has changed in a relatively rapid manner. This rapid change in the stress configuration resulted in a frequent permutation of the principal stress between a horizontal and the vertical direction. This phenomenon points to the interesting possibility of a stick-slip nature of crustal deformation. This can also explain the occurrence of earthquakes with very different stress configuration in the same region (Fig. 2).

## 5. Conclusion

The structural study presented in this paper has revealed a history of multiple extensions in the greater Pearl River Delta region since the end of the Mesozoic magmatism. The collapse of the magmatic arc was associated with formation of molasse basins around large extinct volcanic centers and exhumation of basement along pre-existing NE–SE striking faults. During the early Cenozoic, the area became a passive-margin accompanied by N–S extension, with the Sanshui and the Xinhui Basins forming the major deposition centers. Basaltic volcanism commenced in some basins and extensive exhumation of basement structures occurred in this stage. When the South China Sea began to open, extension on continental crust ceased and the PRD basins entered a stage of tectonic quiescence. Another phase of extension in an ENE–WSW direction began probably in the late Miocene with, when the Xijiang River took a straight course along the normal faults and the morphological framework similar to the present pattern formed in the PRD region. The tectonic history was followed by the Taiwan orogeny, resulting in a dextral motion and the formation of transtensional basins along existing NE-striking faults. The later rifting stages essentially developed along pre-existing faults and it is therefore important to recognize the polyphase nature of the faults in interpreting slip sense indicators.

Throughout the Cenozoic, the maximum principal stress remained vertical to subvertical, and the minimum principal stress direction changed from N–S possibly during the Oligocene to mid-Miocene to ENE–WSW during the mid-Miocene to Pliocene. The basins are not comparable to pull-apart basins developed at bends of transform faults. Rather, they formed as grabens or half grabens resulting from simple extension of the upper crust. The rapid changes in the stress configuration resulted likely from passive reaction of the region to the kinematic motion of neighboring blocks. The extension direction may have changed and permutated in a relatively rapid manner especially in areas of low stress ratios, producing large scale structures showing discordant principal stress directions. While the Taiwan Orogeny produces an essentially E–W directed principal stress, once this stress relaxes, the maximum principal stress flips to a vertical orientation resulting in normal faulting events.

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