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Three-dimensional crustal movement and the activities of earthquakes, volcanoes and faults in Hainan Island, China

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ABSTRACT

Hainan Island is a seismic active region, where Qiongshan *M*7.5 earthquake occurred in 1605 and several seismic belts appeared in recent years, especially the NS trending seismic belt (NSB) located in the northeast part of the island. Here is also a magmatic active region. The lava from about 100 volcanoes covered more than 4000 km^2. The latest eruptions occurred on Ma'anling–Lei Huling volcanoes within 10,000 years. The neotectonic movement has been determined by geological method in the island and its adjacent areas. In the paper, the present-day 3D crustal movement is obtained by using Global Positioning System (GPS) data observed from 2009 to 2014 and leveling observations measured in 1970s and 1990s respectively. The results show the horizontal movement is mainly along SEE direction relative to the Eurasian Plate. The velocities are between 4.01 and 6.70 mm/a. The tension rate near the NSB is less than 1 mm/a. The vertical movement shows the island uplifts as a whole with respect to the reference benchmark Xiuyinggang. The average uplifting rate is 2.4 mm/a. The rates are 2–3 mm/a in the northwest and 3–5mm/a in the northwest. It shows the deformation pattern of the southwest island is upward relative to the northeast, which is different from the result inferred from the coastal change and GPS. Haikou and its adjacent region present a subsidence in a long time. The southern part of the middle segment of the Wangwu-Wenjiao fault uplifts relative to the northern. Meanwhile, the western part uplifts relative to the eastern NSB. The vertical crustal motion and the two normal faults nearly correspond to the terrain. The NSB is located along the Puqiangang-Dazhibo fault, which is assessed as a segmented fault with a dip of 80°–90° and partly exposed. The 3D deformations and other studies reveal the present activities of

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earthquakes, volcanoes and the faults. The small earthquakes will still occur in the NS belt and the volcanoes are not active now.

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1. Introduction

As a continental island, Hainan Island is located in the southern edge of China. The island and its adjacent regions are not only affected by the forces transmitted through the Tibetan Plateau that originates the continuous compressing from Indian Plate, but also the NWW squeeze from the Philippine Sea Plate and the lateral pressure of the N expansion and push from the South China Sea (Fig. 1) [1,2]. Especially the tectonic stress field adjusted locally in the inner island cannot be neglected. Seismic tomographic images indicated a mantle plume may exist beneath and around the island [3]. A sub-vertical low-velocity column is imaged beneath the Hainan and the South China Sea, and extends from shallow depths to 660 km seismic discontinuity and continuously to a depth of 1900 km [4]. The synthetic plumes are even extending down to 2800 km depth [5]. The vertical deformation field has been impacted greatly by the force which originates from the uprising material of the midmantle, even the lowermost mantle. Due to the mantle material upwelling, it caused Yunlong block uplifting. The formation of the geological landforms, the occurrence of earthquakes and other phenomena are closely related to the hot mantle materials [6–8].

Qiongbei depression is one part of the Leiqiong fault depression, and its south boundary is Wangwu-Wenjiao fault (WWF) (Fig. 2). The neotectonic movements of the fault depression are intense. Earthquakes, volcanoes and faults are all very active. Especially in the NS trending seismic belt (NSB) in the northeastern island, 1605 Qiongshan *M*7.5 earthquake (QSE) and several small earthquake swarms occurred (Figs. 2 and 3). The lava erupted from about 100 volcanoes covered an area of more than 4000 km^2. The latest eruptions occurred on Ma'anling–Lei Huling volcanoes (MLV) about 4000–10,000 years ago. The island mainly developed the approximate EW, NW, NE and SN oriented faults [9]. The WWF and some NE, NW oriented faults are active in modern history which affected the formation of the NW oriented uplift and depression directly in the northeast island. The active faults are also associated with the seismic and volcanic activities.

The horizontal and vertical movements were estimated by using geologic method in Hainan and its adjacent areas. The horizontal movement of the island can be found on geomorphologic aspects such as the developed fold, a large number of faults with horizontal shear and the dislocated Quaternary in horizon [2]. For example, the quaternary profile incised by Changliu-Xiangou fault shows a left lateral horizontal slip and slightly distorted formation in some segments [10]. The vertical motion is significant in the north area since the Cenozoic. The crustal movement was inferred by coastal change, Global Positioning System (GPS), leveling and Interferometric Synthetic Aperture Radar (InSAR). The

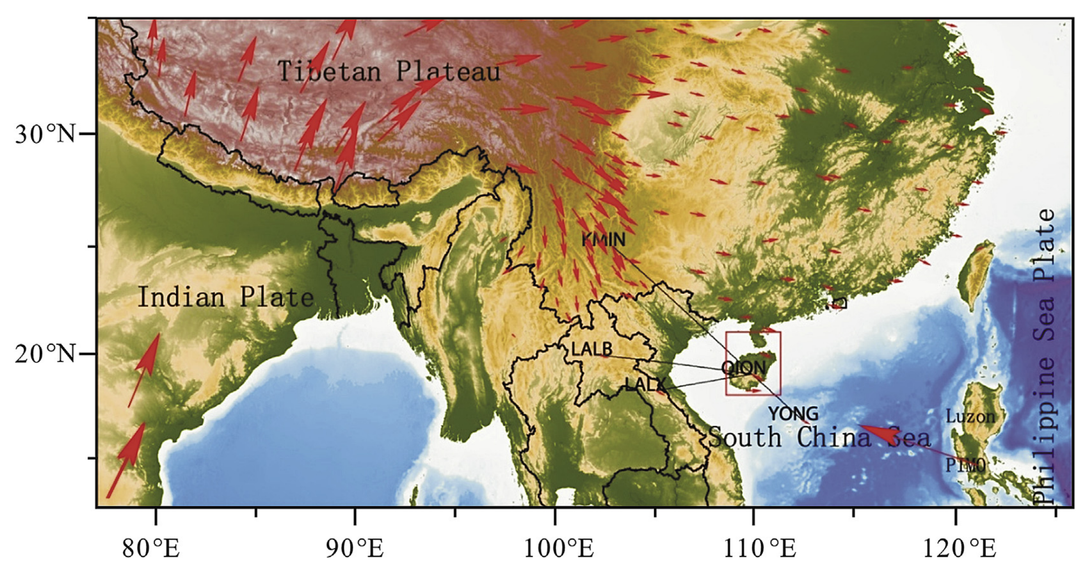

Fig. 1 – GPS velocities relative to Eurasia in the period from 1999 to 2013. The red small box in the inset map shows the study region. Black lines between the two stations are the baselines in Table 1.

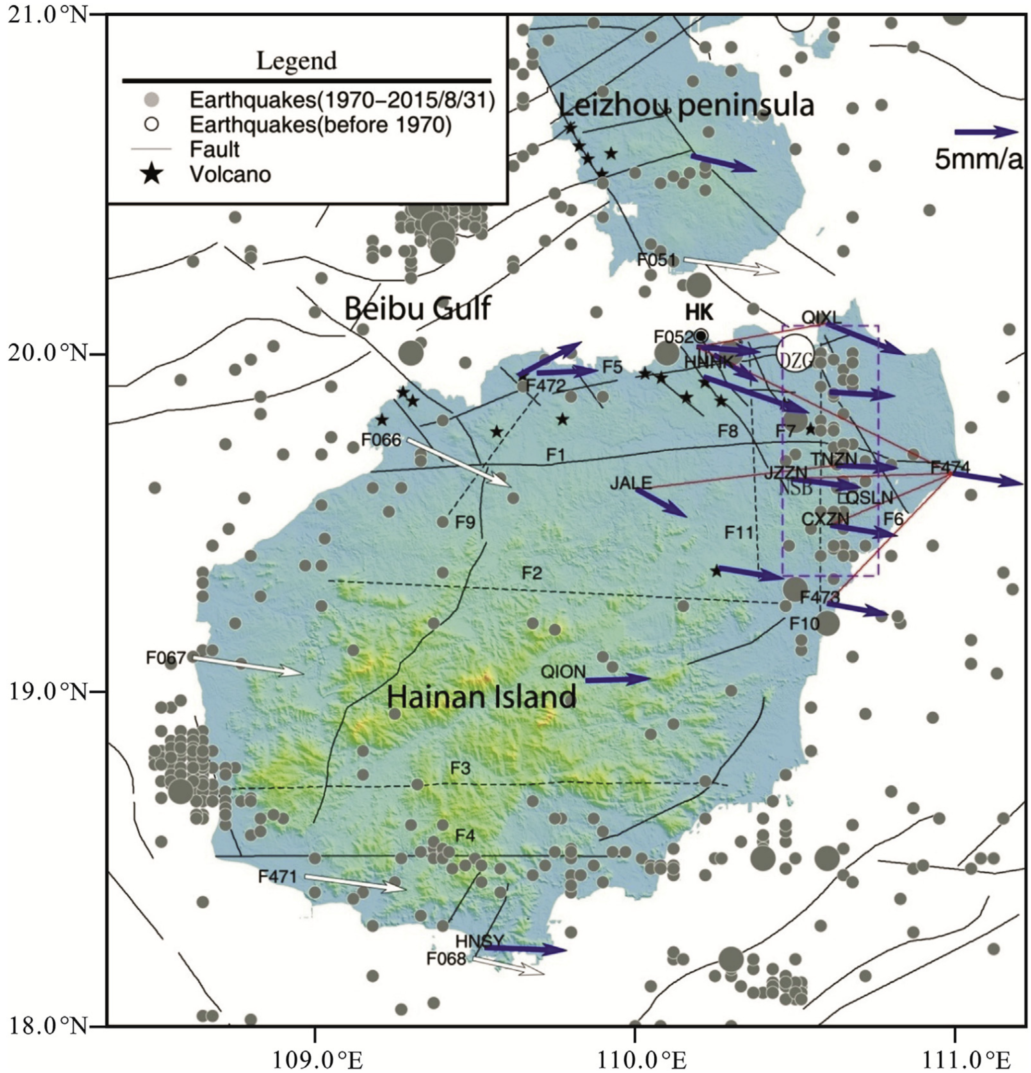

Fig. 2 – GPS velocities relative to Eurasia during 2009–2014 (blue). The velocities during 2009–2013 (white) are from Hu et al. [17]. Red lines between the two stations are the baselines in Table 3. Solid circles are the earthquakes occurred during 1970 and 2015. The open circle denotes the 1605 (M7.5) Qiongshan earthquake. Stars denote volcanic cracters. DZG is Dongzhaigang and NSB is the NS trending seismic belt in the northeastern island. HK (Haikou) is the provincial capital city and observation sites in the paper. The traces denote major faults in Hainan Island and its adjacent. F1, Wangwu-Wenjiao fault (WWF); F2, Changjiang-Qionghai fault; F3, Jianfeng-Wangning fault; F4, Jiussuo-Linshui fault; F5, Manao-Puqian fault; F6, Puqian-Qinglan fault; F7, Haikou-Yunlong fault; F8, Changliu-Xiangou fault; F9, Lingao fault; F10, Puqian-Boao fault; F11, Qiongshan-Shihe fault.

thickness of the deposits is about 4000 m in the depression areas. Dongzhai river became a bay (Dongzhaigang, DZG) because of the coseismic and fast sinking (the 1605 Qiongshan earthquake), continuous decline and widening slowly [11,12]. That was recorded by the tectonic landforms. The movement constrained by the coastal change indicated that the east coast rises relative to the west since the Holocene [2] (Fig. 3). The movement in the north island was also derived by using the precise leveling. The result shows that the east region uplifts with respect to the west [13]. The latest InSAR data presented that there is about 3 mm/a subsidence near NSB [14].

Previous research cannot attain a detail deformation pattern without dense stations and enough data. In the paper, based on GPS observation data measured from 2009 to 2014 and the precise leveling data observed in 1970s and 1990s, the present three-dimensional (3D) crustal movement is studied. Involving in the changes of the coastal rising and descending and other deformation results, the activities of earthquakes, volcanoes and faults are also studied.

2. Horizontal movement

Extensive GPS measurements in the past decades have provided many details of crustal motion in China and surrounding regions [15,16]. The results are that the displacements in west are larger than that in East China in general.

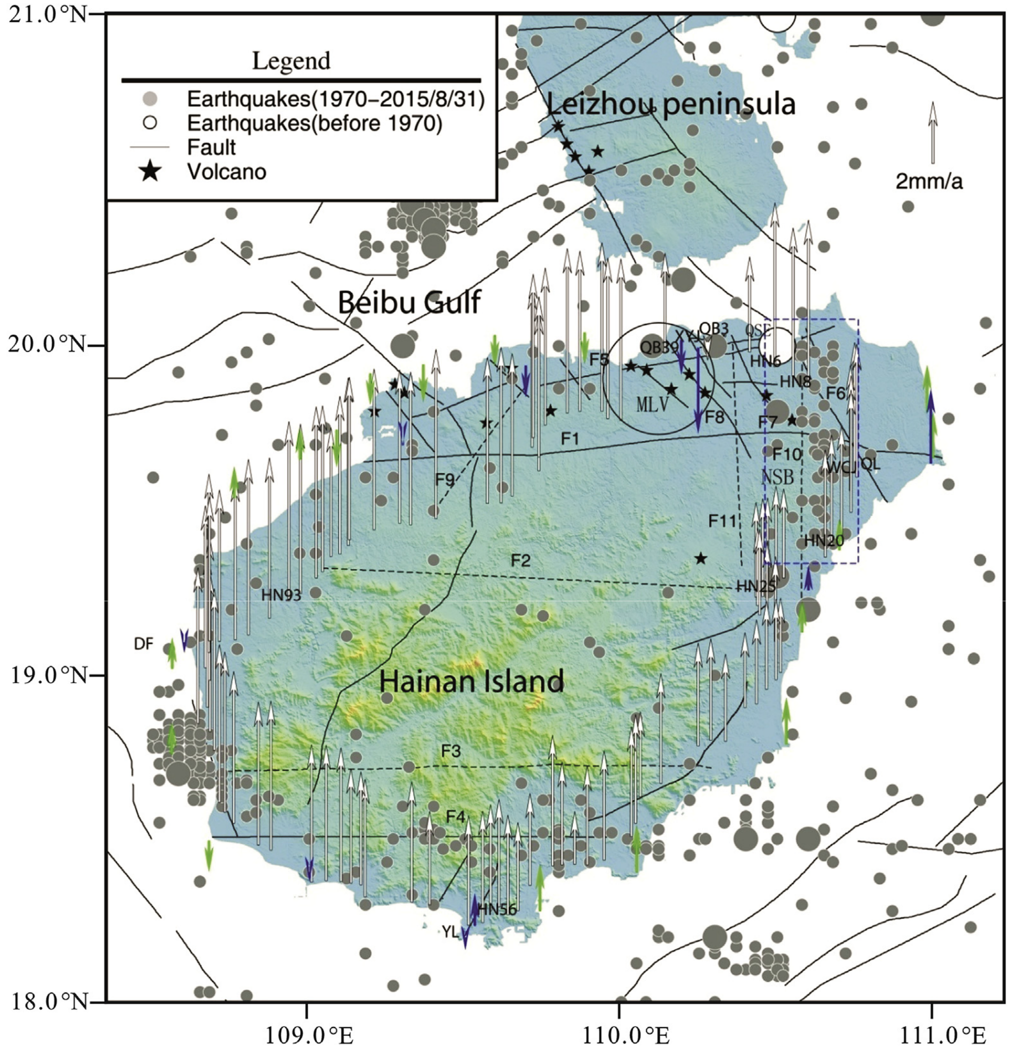

Fig. 3 – Vertical displacement determined by leveling, GPS and the coastal uplift and subsidence. The white rates determined by leveling (1976–1996). The blue rates determined by GPS. The green arrow shows the sketch of the coastal uplift (upward) or subsidence (downward) (from reference [2]). The open circle denotes the 1605 (M7.5) Qiongshan earthquake (QSE). MLV is Ma'anling–Lei Huling volcanoes. DF (Dongfang), YL (Yulin) and QL (Qinglan) are the stations in Table 5. The traces denote major faults in Hainan Island as in Fig. 2.

The South China block, Ordos and Northeast China have been the most stable part with small crustal deformation in Chinese mainland. Here we calculate the horizontal velocity field during 1999–2013. The velocities (Fig. 1) show the change from the west to the east. The two forces are obvious, one is the push from the Indian Plate transmitted by the Tibet Plateau and the other one is the compression from the Philippine Sea Plate. Hu et al. [17] have studied the horizontal movement during 1999–2007. It was based on eight stations distributed on the edge of the island. The results show the stations move toward SEE direction relative to Eurasia Plate and are consistent with the movement of the South China block. The thrust of the Luzon islands to the center basin of South China Sea in NW direction is stronger than that of the Philippines Sea Plate to southern China block in NWW direction [18]. On the edge of the northwest of Beibu Gulf, the compressive strain is the strongest in the NNW direction. It can be proved by the shortening of the GPS baselines (Table 1). The baseline shortened at a rate of −8.09 mm/a. The two $M > 6$ earthquakes occurred here in 1995 (Fig. 2).

Table 1 – Change of baselines (dL) in China and surrounding regions.

Baseline	dL (mm/a)	Time period (year)
KMIN-QION	−8.09	2011–2014
LALB-QION	5.70	2009–2014
LALX-QION	13.22	2009–2014
QION-YONG	−3.42	2011–2014

In the north of the island, the campaign GPS observations of the 15 stations which covered the main volcanoes and fault zones were carried out from 2009 to 2014 (Fig. 2). There are ten stations among them were built in 2008 or 2009 to monitor the volcano. The data quality of the two stations, QSLN (built in 2008) and F474 (one of the Crustal Movement Observation Network Of China (CMONOC), built in 2007) which are located in the east of NSB are checked using translating, editing, and quality checking (TEQC) [19] (Fig. 2 and Table 2). It illustrates that the QSLN were in a bad environment where the satellite signals were obstructed by trees and buildings. The values of MP1/MP2 are larger than that of the stations observed by International GNSS Service (IGS). The quality checking (QC) statistics suggest that there are about two-thirds of IGS stations which MP1, MP2 are less than 0.5, 0.75 respectively. The percentages (*P*, complete observation/possible observation) above 10° elevation are also considered as a factor to estimate data quality. According to the provisions of Crustal Movement Monitor [20], the percentage of the GPS reference stations should be more than 85%, the percentage of the GPS campaign stations should be more than 80%. The percentages of QSLN are less than 80%. Since less observation data being received, we do not analyze the site QSLN, while another station F474 in the east of NSB is used in the paper for a good observation environment and better data quality.

The velocities of the 15 stations are from 4.01 to 6.70 mm/a in the SEE direction which is consistent with other results based on GPS in the past decades [15,17] The rates of baselines between the two stations become larger from 2009 to 2014 (Table 3). It shows that the crust is extensional, indicating that the regional stress field is extensional in the horizontal direction [21]. In NSB, the changes of the baseline lengths, F474–JZZN and F474–CXZN, are less than 1mm/a.

3. Vertical movement

3.1. *Vertical deformation derived by GPS and leveling*

The crustal uplift and subsidence of the island is frequent and intermittent in different geologic time. It can be demonstrated by the multistage planation surfaces and discontinuous deposition [2,22]. The presently geodetic observation method is one of the most effective way to monitor the deformation. The vertical velocities are calculated using GPS observations, which are no less than three periods from 1999 to 2014 (Table 4 and Fig. 3). It shows that the east coast in the northern island rises relative to the west coast apparently, while the southern island subsides slightly. The site QION locates in the center is stable. HNHK in the north subsides and HNSY in the south of the island uplifts relative to QION. The GPS results are similar to that of the coastal change (Fig. 3 and section 3.2).

The vertical movement is also detected by using the precise leveling survey. The leveling route circled Hainan Island and the precise leveling surveys were carried out in 1970s (1976, 1977 and 1979) and 1990s (1995 and 1996) with a period of nearly 20 years. Totally, 101 benchmarks were observed repeatedly. We calculate the vertical deformation rates with the method of Linear Kinematic Adjustment Model [13,23]. The reference point is benchmark Xiuying. The average uplifting rate is 2.4 mm/a with average uncertainty of

Table 2 – Observation surrounding and data quality of QSLN and F474 checked with TEQC.

Station	*P* (2009) (%)	*MP1* (m)	*MP2* (m)	*P* (2014) (%)	*MP1* (m)	*MP2* (m)	Observed pictures (taken in 2014)
QSLN	79	0.73	0.73	66	0.78	1.05	
	80	0.76	0.72	64	1.00	1.06	
	80	0.71	0.71	68	0.72	0.86	
F474	96	0.40	0.44	92	0.53	0.58	
	97	0.44	0.44	89	0.61	0.61	
	97	0.43	0.45	95	0.46	0.46	
				96	0.45	0.45	

Table 3 – Changes of baseline lengths (*dL*) in the volcano and fault zones.

Baseline	*dL* (mm/a)	Time period (year)	Baseline	*dL* (mm/a)	Time period (year)
F474–F052	4.46	2009–2014	F474–F473	2.81	2009–2014
F474–JZZN	0.30	2009–2014	F052–QIXL	3.83	2009–2014
F474–CXZN	0.92	2009–2014	JALE–TNZN	3.79	2009–2014

Table 4 – Vertical displacement determined by GPS.

No.	Stations	*Vu* (mm/a)	Observation time or time period (year)
1	QION	0.00	2008.2–2016.1
2	HNSY	1.05	2010.7–2016.1
3	HNHK	−2.76	2010.6–2016.1
4	F052	−1.12	2004/2007/2009/2011/2013
5	F472	−1.02	2009/2011/2013
6	F066	−0.01	1999/2004/2007/2009/2011/2013
7	F067	−0.34	1999/2004/2007/2009/2011/2013
8	F471	−0.29	2009/2011/2013
9	F068	−0.40	1999/2004/2007/2009/2011/2013
10	F473	0.79	2009/2011/2013
11	F474	2.40	2009/2011/2013

Table 5 – The rates of the coastal rising and descending detected by the record in the tide-gauge stations (from reference [34]).

Tide-gauge stations	Time period (year)	Rates (mm/a)
Yulin (near Sanya)	1954–1983	0.4
Dongfang	1965–1988	0.6
Qinglan	1976–1989	4.4
Haikou (old and new station)	1953–1992	−2.0
Haikou (new station)	1976–1992	−4.1

1.63 mm/a, which is much smaller than the ground deformation.

The uplift movement of the island agrees with other results [24] (Figs. 3 and 4). The rates of the northwest leveling route from Xiuying to Sanya are 2–3 mm/a. The minimum rate is 1.64 mm/a (HN25), while the northwest route from HN56 to QB39 uplift at the rate of 3–5 mm/a. The maximum is up to 5.78 mm/a (HN93). The west of the island uplifts relative to the east. It is different from the results constrained by GPS and the coastal change [2] and also disagreed with the leveling results of the tilt from the southeast to the northwest island in 1979–1957. Possibly, the observation sites have different locations and stress from surroundings.

In Fig. 4, the elevations are within 50 m between XYJ and the benchmark whose distance is about 570 km, then the land get higher and undulating. Most of the benchmarks move with the topography during 1970s–1990s. From 425 km to 565 km (DF and its adjacent region), the movement of benchmarks are opposite to the topography. Haikou and its adjacent regions are sinking. The maximum rate of the special subsidence is −2.72 mm/a (QB3), which is similar with the GPS result. The region always sank studied by other researchers. Zhang et al. [25] studied the leveling in Wenchang-Haikou. It showed decline and Haikou has the largest descending rate which was up to 4 mm/a (1957–1977). Xu [26] investigated the sinking rate is about 14–10 mm/a in Haikou and its adjacent regions and DZG recently. We speculate that the sharp sink may be caused by the rapid city construction and/or groundwater exploitation, which can cause the subsidence at about 1–1.5 cm/year by the other researches [27,28].

The leveling shows the movement pattern on the boundary of Hainan Island. Other more detail deformation in the north of the island has been studied by other researchers (Fig. 5). The repeated observations from 1957 to 1969 show that the modern crustal uplift in the southeastern is the most significant. The rise rate in Yunlong is up to 3.7 mm/a [29]. The average rate is 0.76–1.2 mm/a in Haikou-Wenchang (HW) (1957–1969). The rate is 0.6 mm/a in Haikou-Chengmai-Jiale (HCJ) (1970–1977), which agrees with the result of the long trend of crustal deformation reflected by the coastal sediments during the late Pleistocene and Holocene [26]. Analyzing the repeated observations from 1957 to 1982 in Qiongbei, the regional deformations are different in the two parts of Xiuying-TunChang (HT). The east area uplift while the west area subside [13]. The east part of Puqian-Qinglan fault rise relative to the west which is consistent with the results of Li Ping [30] who thought the normal faults control the development of DZG in a long time. The artificial earthquake sounding suggests that the DZG is a graben structure. The faults are along the two sides respectively and their dips are opposite. The displacement in the west fault is 400 m, which is greater than the east (150 m) [31]. There is a basement fracture along the NNW direction.

The WWF is divided into three segments (west, middle and east segments) by Lingao and Changliu-Xiangou fault. The deformation in the period between 1974 and 1982 shows that it has slight extension and sag in the middle segment of WWF (Fig. 6a). The other segments were not active obviously. The

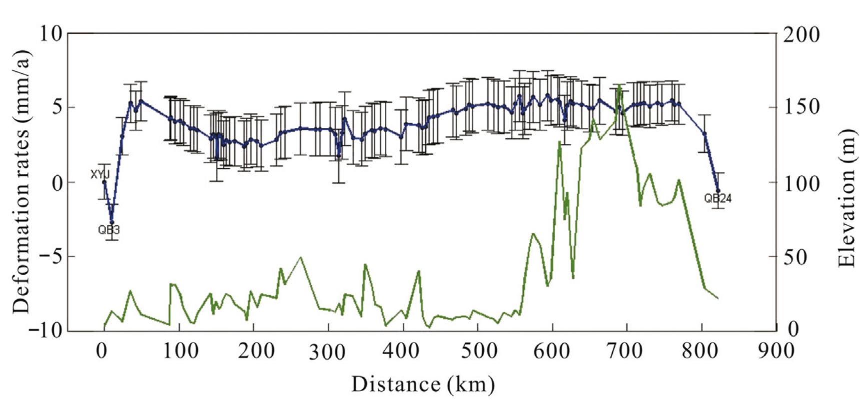

Fig. 4 – Vertical deformation rates with error bars detected by precise leveling in the period from 1970s to 1990s (Blue line). The green line is the elevations.

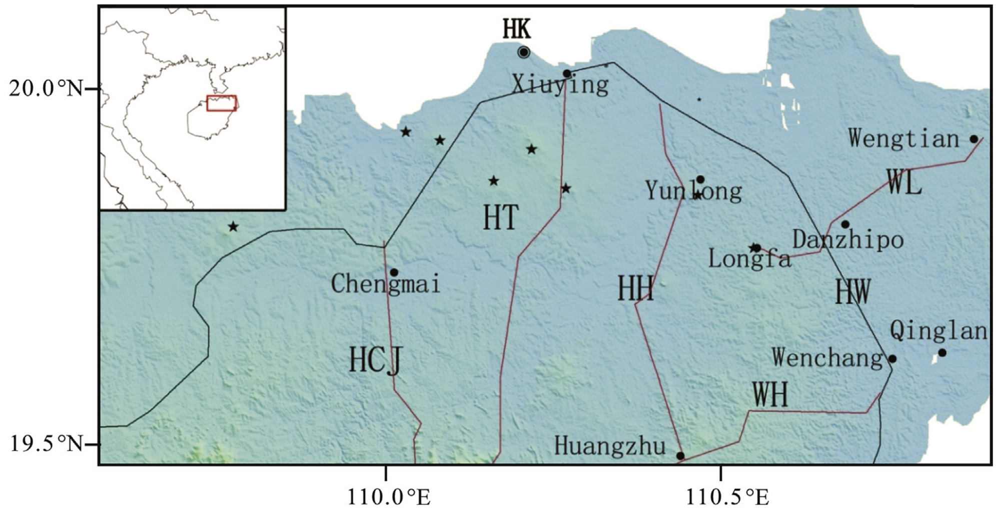

Fig. 5 — Some leveling routes of the previous studies. HCJ, Haikou-Chengmai-Jiale; HT, Haikou-TunChang; HH, Haikou-Huangzhu; HW, Haikou-Wenchang; WL, Wengtian-Longfa; WH, Wenchang-Huangzhu. The red small box in the inset map shows the study region.

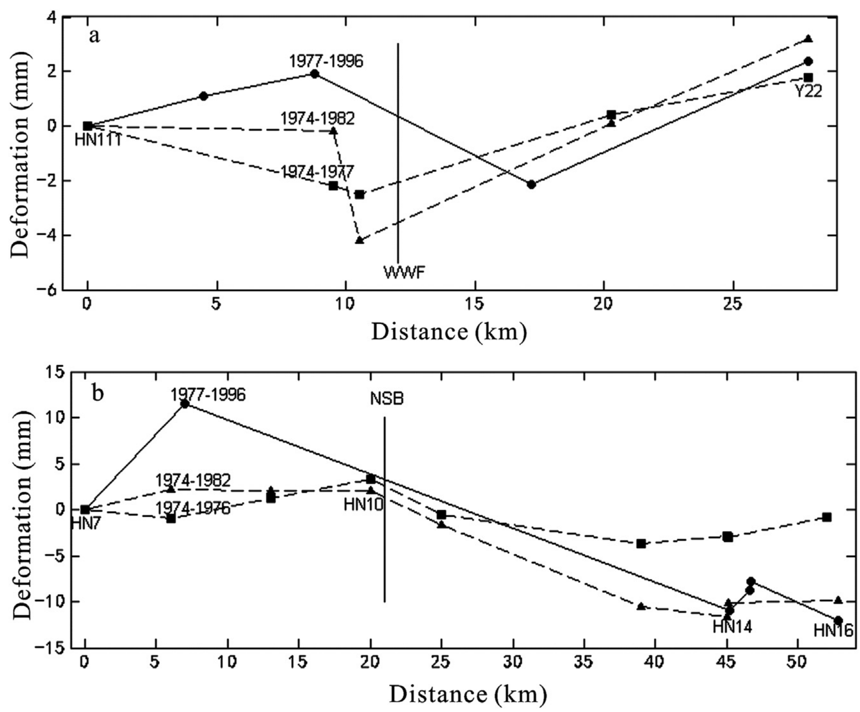

Fig. 6 — a) Vertical deformation from south to north for three periods. The deformation during 1974–1982 and 1974–1977 is from reference [13]. b) Vertical deformation from the west to east for three periods. The deformation during 1974–1982 and 1974–1976 is from reference [13].

new leveling profile crosses the middle segment of the fault. The normal fault moved as the south rised and the north subsided in 1977–1996 (Fig. 6a). They were still subsiding near the fault as other two periods in 1974–1977 and 1974–1982 [13]. The different changes of the deformation indicate that the regional movement changes with time.

The leveling also crosses the NSB. The small earthquake swarms in a narrow zone of about 63 km long and 13 km wide [21]. Unfortunately, no dense benchmarks with repeat observation distributed near the NSB during 1970s–1990s. From the farther and sparse sites, we think that the movement is obviously different on both sides of the NSB in 1977–1996 (Fig. 6b). The average uplift rate in the eastern part of NSB is about 5 mm/a (HN7–HN8) while the rate of 4 mm/a in the western part from WCJ to HN20. The maximum difference is up to 2.5 mm/a. The result agrees with the coastal change and the deformation during the other two periods 1974–1976, 1974–1982, which showed that the subsidence was between HN10 and HN14. The results are the same as that the east of DZG has large uplift, while a large subsidence presents in or near the region. The normal fault shows a corresponding movement that the east part dropped continuously and formed the sedimentary basins.

3.2. *Vertical deformation derived by coastal changes*

The topography suggests that the vertical movement is different in the two sides of the WWF. The south area of the Qiongzhong has been uplift 1500 m relative to the north area, the Leiqiong has been subsidence since the Neogene (Figs. 2 and 3). Within the first structural unit, the secondary unit is further divided by the faults or the large difference between the uplift and depression. The coastal change can be reflected by the sea level [29]. Based on the data observed in the tide-gauge stations from 1953 to 1992, the coastal movements are shown in Table 5 [26]. The result shows that the east, west and south of the coast continued to uplift, which is consistent with the results of field observations. However, the tidal station Haikou (HK) in the north coast of the island is subsidence, which is supported by GPS and leveling results. The rate of Qinglan is up to 4.4 mm/a and is much larger than others' rates. The rising trend is consistent with the present movement derived from GPS and leveling. Because they have different position and reference points, we cannot compare them quantitatively.

The coastal uplift and subsidence in the east of Qiongbei shows that the east bank of DZG was rising while the bay and its adjacent regions sank significantly. The vertical deformation was once caused by the strong earthquakes. The area of the subsidence was over a hundred square kilometers in the northern coastal areas. The 72 villages sank in the sea in QSE. The coseismic subsidence was about 3–4 m with the maximum value up to10 m. According to the investigation of the coastal changes in nearly 50 years, the northwest bank subsided at the average rate of 3–4 mm/a [32]. The data recorded in Xiuying station from 1953 to 1993 shows that the change of tidal levels was limited to 12 cm, so the rising of water level was due to the crustal subsidence in DZG [11].

The average rate is about 0.61 mm/a in the late Pleistocene and Holocene in the southeast coast and is consistent with results obtained by a lot of littoral facies sediment samples [26]. Based on the studies on the coral reef samples, the depths of sediment and paleo sea level indicators in the south coast, the results show that the rates became -0.1 ± 0.6 or 1.4 ± 0.3 mm/a in 5000 (4000) years ago. The crustal movement became slow [33].

4. Discussion and conclusion

4.1. *Seismic activity*

The distribution of the earthquakes is divided into three zones (north, middle and south zone) by two EW trending faults, WWF and Jianfeng-Wangning fault. The earthquakes are active in the north and south zones. They are shallow epicenters and more active in the north zone than the south. Since 1969, the earthquakes can be recorded by the seismic network. The relocation results from 820 earthquakes ($M_L \geq 1.0$) occurred during 2000–2012 show that the earthquake swarms concentrated in the faults. One of them concentrated is the NSB. The depth of the earthquakes are constrained 5–15 km [1,21,35]. The earthquakes are related to the hot mantle material. The Dongfang earthquakes occurred in 1992 were considered related to the deep magma intrusion.

The distribution of NSB is not along Puqian-Qinglan fault. The low velocity anomalies are only at the depth of about 5 km in the NW faults. It shows that although they are more active, the depth of the movement is shallow [1]. It is shallower than the depth of the earthquake. We do not think the modern earthquake swarm is related to the NW trending faults. The QSE is involved in the uprising mantle plume. We consider the hot mantle material will still be a main reason that caused earthquakes in the island and its surrounding regions. We identify both the present-day corresponding motion near NSB and the deep thermal material will cause some small earthquakes. The crustal uplift in Dongfang is inconsistent with the terrain and it will be another possible location for next earthquakes.

4.2. *Volcano activity*

The volcanic activity is intensive in Leiqiong, where the volcanoes are almost erupted in the Quaternary except a few erupted in the Tertiary. In the northern of Hainan Island lava covered more than 4000 km^2 [36]. These volcanoes are located in the developed regions with large populations. MLV lies in Qiongshan and is only about l5 km away from Haikou (the provincial capital). The city volcanoes have typically potential risk of eruption [37]. It is about 35 km away from the 1605 Qiongshan earthquake. The inversion results with the receiver function show that the velocity is very low in the lower crust and upper mantle, which may be related to the thermal motion of the seismic station in the crater.

There is no larger difference among the stations in present horizontal movement. The vertical deformation indicates little specific movement. So the volcanic regions have no significant deformation and earthquake swarms now. Combining with the results of geomagnetism, volumetric strain, geothermics and the upper mantle structure in the region [36,38], we preliminarily estimate that the activity of the deep magma in the Holocene volcanoes are not active.

4.3. *Fault activity*

The activity of the EW, NW, NE and SN oriented faults in the northeast area is more active than that of the northwest area of the island, while in the northeast area those faults located in the south is also more active than that at the north. The EW and NW trending faults are the most active. The soil oxygen measurements across the faults show that both the WWF and Puqian-Qinglan fault are more active today [39].

The Puqian-Manao fault with NEE trend which located in the north of the Qiongzhou Strait is segmented by the NW oriented faults and becomes discontinuously. It was more active in Quaternary and can be divided into east, middle and west segments. The QSE occurred in the intersection part of the east of the fault and Puqian-Qinglan fault [40].

The NS oriented faults are extending about 100 km from north to south and about 35 km from east to west. It consists of the faults such as Qiongshan-Shihe and Puqian-Boao [9]. Less studies were carried out on their parameters and activity. The NSB is located in the middle and north of the region with the low velocity anomalies, which may be revealed the crushed and broken in the crust and lithosphere [1]. The small earthquake swarms along the middle and north of the Puqian-Boao fault. The 3D deformation shows that there is subsidence and slight extension now. We consider the north segment of the Puqian-Boao fault is the corresponding motion.

4.4. *Deformation simulation of the NSB*

The NSB is just the boundary between the Quaternary volcanoes to the west and the sedimentary basin to the east, and it is the largest difference between ascending and descending. It is a normal fault with a high dip angle. The researchers had attained the different parameters shown as Table 6 [41]. Liu et al. assumed that it is due to the magma intrusion in a vertical dyke or a tensile fracture expanded. The parameters of the NSB were also inversed by the small earthquake location and the regional stress direction [21]. The dyke intrusion or tensile fracture expansion was observed by InSAR. The residuals between the observation and the model indicate that it is not a simple dyke [14].

The vertical deformation near the fault is shown in Fig. 7. The sinking zone is about 5–14 km in width. From the average depth of earthquakes (about 10 km), the layer of slow velocity anomalies (25 km and 35 km) and smaller and limited change of the water level and temperature in the well near the fault, we induce that the deformation can be affected by both the fault motion in the lower crust and the thermal material migration in the deep. The pressure source is more complicated. The thermal material did not upwell to the shallow. We consider the crustal movement of the fault represents corresponding motion and involved in the hot material in the deep. Comparing the leveling surveys with the crack model [42], we estimate the fault is a segmented with a dip of 80°–90°.

4.5. *Conclusion*

The horizontal movement is mainly SEE direction relative to the Eurasian Plate at 4.01–6.70 mm/a in Hainan Island. There is a tension rate less than 1 mm/a near the NSB. The vertical movement shows that the island uplifts as a whole with respect to the reference benchmarks, and the average uplifting rate is 2.4 mm/a. The southwest area uplifted at 1–2 mm/a relative to the northeast during 1970s–1990s. The deformation pattern is that the southwest island is upward relative to the northeast. The new result is opposite to the previous results derived from the coastal change and GPS, which sites located at the edge of the island. The west uplifts relative to the east of NSB and depression in the NSB. The southern part of the middle segment of the WWF uplifts relative to the north. We infer the terraces and the two normal faults represent corresponding motion. The NSB is located along the Puqian-Boao fault, which is assessed as a segmented fault with dips of 80°–90°. The 3D deformations and other research results reveal that the small earthquakes may occur in the NSB in future and the volcanoes are not active now.

Table 6 – Parameters of dyke or fault for the best-fitting models.

Strike (°)	Dip (°)	Length (km)	Width (km)	Opening (m)	The upper (km)	Lower bound (km)	References
				1		8–20	[41]
3	83	63	13		2	15	[21]
N7.4W	71	54	1	1	0	25	[14]

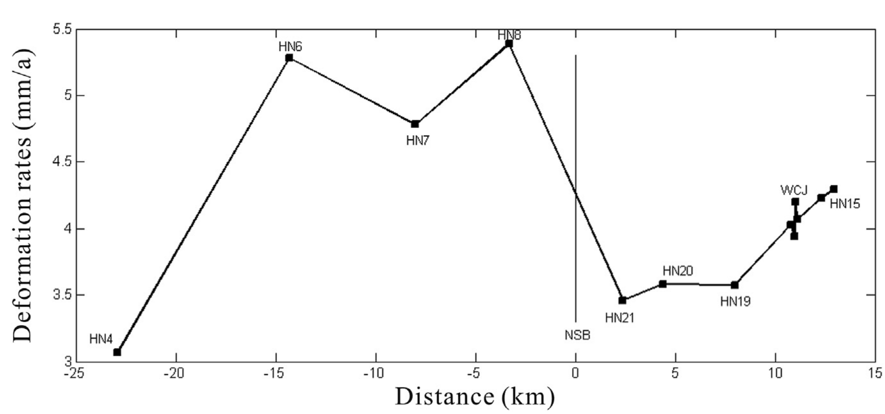

Fig. 7 – Vertical deformation rates detected by precise leveling across the NSB. The solid line is the presumed fault. The distances are between the benchmarks and the center of the NSB.

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