Acta Oceanol. Sin., 2024, Vol. 43, No. 2, P. 83–93
https://doi.org/10.1007/s13131-023-2198-2
http://www.aosocean.com
E-mail: ocean2@hyxb.org.cn

U-Pb zircon geochronology of basaltic pyroclastic rocks from the basement beneath the Xisha Islands in the northwestern South China Sea and its geological significance

Yu Zhang[1, 2, 3], Kefu Yu[1, 2, 3*], Shiying Li[4]

[1] Guangxi Laboratory on the Study of Coral Reefs in the South China Sea, Guangxi University, Nanning 530004, China

[2] Coral Reef Research Center of China, Guangxi University, Nanning 530004, China

[3] School of Marine Sciences, Guangxi University, Nanning 530004, China

[4] Key Laboratory of Ocean and Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Science, Guangzhou 510301, China

Received 17 November 2022; accepted 27 March 2023

Abstract

As one of the micro-blocks dispersed in the South China Sea (SCS), the basement of the Xisha Islands has rarely been drilled because of the thick overlying Cenozoic sediments, which has led to a confused understanding of the pre-Cenozoic basement of the Xisha Islands. Well CK-1, a kilometer-scale major scientific drill in the Xisha Islands in the northwestern SCS, penetrated thick reefal limestone (0–888.4 m) and the underlying basement rocks (888.4–901.4 m). In this study, we present the zircon U-Pb ages of basement basaltic pyroclastic rocks from Well CK-1 in the Xisha Islands of the northwestern SCS to investigate the basement nature of the Xisha micro-block. The basement of Well CK-1 consists of basaltic pyroclastic rocks on the seamount. The zircon grains yielded apparent ages ranging from ca. 2 138.9 Ma to ca. 36 Ma. The old group of zircon grains from Well CK-1 was considered to be inherited zircons. Two Cenozoic zircons gave a weighted mean $^{206}Pb/^{238}U$ age of (36.3 ± 1.1) Ma, Mean Squared Weighted Deviations (MSWD) = 1.2, which may represent the maximum age of the volcano eruption. The Yanshanian inherited zircons (116.9–105.7 Ma and 146.1–130.2 Ma) from Well CK-1 are consistent with the zircons from Well XK-1, indicating that the basement of Chenhang Island may be similar to that of Well XK-1. We propose that the Xisha micro-block may have developed on a uniform Late Jurassic metamorphic crystalline basement, intruded by Cretaceous granitic magma.

Key words: South China Sea, Xisha Islands, basaltic pyroclastic rocks, zircon

Citation: Zhang Yu, Yu Kefu, Li Shiying. 2024. U-Pb zircon geochronology of basaltic pyroclastic rocks from the basement beneath the Xisha Islands in the northwestern South China Sea and its geological significance. Acta Oceanologica Sinica, 43(2): 83–93, doi: 10.1007/s13131-023-2198-2

1 Introduction

Knowledge of the basin basement provides important evidence for the inversion of the basin's tectonic evolution and is an important part of basic geological research on the basin. Studying on the composition and properties of the basement can provide an important theoretical basis for discussing the relationship between adjacent plates, tectonic characteristics, formation mechanisms, and the tectonic evolution of adjacent areas (Xu et al., 2007; Zhang et al., 2007; Guynn et al., 2012; Zhao and Zhai et al., 2013; Xie et al., 2014; Tang et al., 2017). Furthermore, the basement is the material basis for the formation and evolution of sedimentary basins and is also related to the formation of overlying basins and their hydrocarbon-bearing properties. The basement controls the sedimentary pattern and genetic mechanism of the basin and the type and distribution of hydrocarbon traps in the sedimentary basins (Chen et al., 2005; Liu et al., 2004a, 2004b, 2011; Deng et al., 2005; Gao et al., 2007; Li et al., 2012; Mora-Bohórquez et al., 2017; He et al., 2017). Therefore, scientific research on basin basements is not only helpful for studying the formation of sedimentary basins but also has important guiding significance for studying the tectonic evolution process of adjacent plates.

The South China Sea (SCS) is one of the largest marginal sea basins of Eastern Asia, which is located at the junction of the Pacific Plate, the Eurasian Plate, and the Indo-Australian Plate (Lin et al., 2009; Guo et al., 2016a; Sun, 2016; Zhang et al., 2018, 2020a, 2020b; Miao et al., 2021). Although the SCS basin is small and young, the SCS has almost experienced a complete Wilson cycle (Li et al., 2013; Fang et al., 2017; Wang et al., 2016; Yang and Fang, 2015; Zhang et al., 2020b). Therefore, the SCS is considered as a natural laboratory for the study of many lithospheric processes such as continental break-up, ocean basin expansion, and subduction (Li et al., 2013, 2015; Yan et al., 2008c, 2010).

Because of the thick Cenozoic sediments overlying the continental basement in the northern SCS, the continental basement has rarely been drilled. As a result, there is a confused un-

Foundation item: The National Natural Science Foundation of China under contract Nos 42030502, 42090041 and 42166003, the Guangxi Scientific Projects under contract Nos AD17129063 and AA17204074, the Guangxi Youth Science Fund Project under contract 2019GXNSFBA185016; the Ph.D. Research Start-up Foundation of Guangxi University under contract No. XBZ170339.
*Corresponding author, E-mail: kefuyu@scsio.ac.cn

derstanding of the pre-Cenozoic continental basement of the northern SCS (Liu et al., 2004a, 2011; Lu et al., 2011; Sun et al., 2014; Xiu et al., 2016; Zhu et al., 2017). The International Ocean Discovery Program Expedition (IODP) 367/368 expeditions suggest that the basement of the Liwan sub-basin consists of fore arc-inherited anisotropic meta-sediments (Zhang et al., 2020c). Some scholars have identified a Precambrian metamorphic crystalline basement in the northern SCS based on geophysical data (Compiled by the Second Marine Geological Investigation Brigade of the Ministry of Geology and Mineral Resources, 1987; Liu and Zhan, 1994; Yao and Wan, 2006; Hao et al., 2009; Lu et al., 2011; Sun et al., 2014). Previous researchers have obtained gneiss from the Pearl (Zhujiang) River Mouth Basin of the northern SCS; however, high-precision dating data are still lacking. At present, it is uncertain whether gneiss is the product of a Precambrian crystalline basement or late tectonic metamorphism (Sun et al., 2014).

Well XY-1, located on Yongxing Island, was the first well to penetrate reef limestone and reach the metamorphic crystalline basement of the Xisha Islands. The basement rocks are mainly composed of granitic gneiss and biotite plagioclase gneiss with an Rb-Sr age of 627 Ma (Wang et al., 1979). Based on the Rb-Sr age of Well XY-1 (627 Ma), some researchers have proposed that the northwestern region of the SCS developed on top of a Precambrian crystalline block (Liu and Zhan, 1994; Liu et al., 2004a, 2011; Yue et al., 2013; Sun et al., 2014).

The age of the metamorphic rocks in Well XY-1, as determined by bulk Rb-Sr analysis, is likely to have no specific geological significance (Zhu et al., 2017). According to the data from Well XY-1, both orthometamorphites and parametamorphites were present (Sun, 1987). The analyzed sample from Well XY-1 may not have been a typical orthometamorphite. The resulting Rb-Sr isochron line was derived from multiple samples that generated older ages (Sun, 1987). Sun (1987) redated the basement rocks of Well XY-1 and obtained the K-Ar age of (96.341 1 ± 1.18) Ma, which represents the age of the last metamorphic event, and proposed that the Xisha basement formed between 627 Ma and 96 Ma (Sun, 1987). Well XK-1, located 1 km from XY-1, is another deep well that penetrates the reef limestone. Zircon U-Pb dating indicates that the basement rocks are Late Jurassic plagiogneisses [(152.9 ± 1.7) Ma], which were intruded by Early Cretaceous granitic magma [(107.8 ± 3.6) Ma] (Zhu et al., 2017).

Whether the northern SCS developed on top of a uniform Precambrian metamorphic crystalline basement remain controversial. In this study, we present the LA-ICP-MS zircon U-Pb ages of basaltic pyroclastic rocks from Well CK-1, Chenhang Island, Xisha Islands, SCS, to determine the time of magmatic activity. In addition, a comparison of magmatic activity in the SCS and surrounding areas enabled us to identify the basement nature of the Xisha Reef Islands.

2 Geological setting and sample description

According to bathymetric, gravity, and magnetic maps, the SCS basin can be divided into three sub-basins: Northwest sub-basin, East sub-basin, and Southwest sub-basin. Based on a seafloor magnetic survey, the East sub-basin is the largest sub-basin formed by north–south extension (Briais et al., 1993; Taylor and Hayes, 1982). More recently, constrained by an investigation of the IODP 349, the onset of seafloor spreading began at 33 Ma. Seafloor spreading stopped at approximately 15 Ma in the East sub-basin, and about 16 Ma in the Southwest subbasin (Li et al., 2014, 2015). A southward-spreading ridge jump occurred around 23.6 Ma in the East sub-basin (Li et al., 2014).

Several micro-blocks are dispersed within the SCS, including the Xisha, Zhongsha, Dongsha, Nansha, and Reed-Northeastern Palawan blocks (Li et al., 2013; Liu et al., 2004a, 2011; Yao et al., 2004; Zhang et al., 2018, 2020b; Yan et al., 2008b, 2010, 2014, 2015). Previous studies have suggested that the continental basement is widely distributed across all micro-blocks (Yan et al., 2010 and references therein). These micro-blocks were considered as a whole in a large micro-block during Paleo-Tethys times, which was named the "Qiongdongnan block" (Liu et al., 2002, 2006). These blocks began to separate from each other because of thinning and extension of the SCS lithosphere during the Late Cretaceous (Liu et al., 1999; Yao et al., 2004; Xiu et al., 2016). The Xisha micro-block, located in the northwest part of the northern continental slope of the SCS, is bounded by the Qiongdongnan Basin in the northwest, the Xisha Trough in the north, and the Dongsha Trough in the east. It is a thinned continental crust, and its basement may have been affected by multi-stage magmatism (Qiu et al., 2006; Huang et al., 2011a, 2011b; Guo et al., 2016b; Xiu et al., 2016).

Well CK-1 which is located just 20 m from Well CK-2, was drilled on Chenhang Island of Xisha Islands from an altitude of +1.0 m to a bottom depth of 904.14 m (Fig. 1). The Well penetrated thick reefal limestone (0–888.4 m) and underlying basement rocks (888.4–901.4 m). The basement of Well CK-1 consisted of basaltic pyroclastic rocks. The basaltic pyroclastic rocks are gray–green in color. They were extensively weathered and exhibited the vesicular and amygdaloidal structures under a microscope. The amygdalae were mainly oval and round in shape, with a few irregular ones in some parts, and the filling minerals were mainly calcite, opal, chalcedony, and zeolite. The main crystalline clastic mineral was clinopyroxene, with a small amount of plagioclase (Fig. 2). The crystal clastics are usually subangular or angular in shape, indicating that the basaltic pyroclastic rocks are in situ or nearby volcanism. In addition, there were a few marine fossils in the basaltic pyroclastic rocks. Li et al. (2019) studied the mineral chemistry of clinopyroxene in basaltic pyroclastic rocks in Well CK-1. The clinopyroxenes are mainly composed of diopside, which have high Al_2O_3 (5.54%–10.20%), CaO (21.88%–22.62%) and low SiO_2 (41.40%–48.44%) contents and high Al^{IV}, indicating that parental magma of the basaltic pyroclastic rocks belongs to a silica-undersaturated alkaline series. The Ca, Fe, and Ti concentrations increased from the core to the rim, indicating that the evolution trend of the host magma of pyroxene coincided with that of the alkali rock series. Clinopyroxene discrimination diagrams show that the parental magma formed in an intraplate tectonic setting (Li et al., 2019). LA-ICP-MS analysis of clinopyroxenes in basaltic pyroclastic rocks from Well CK-2 suggested that the parental magma was characterized by high temperature, low pressure, and low oxygen fugacity (Zhang et al., 2018). We collected a 3 kg basaltic pyroclastic rock sample from Well CK-1. The selected samples were weakly weathered.

3 Analytical methods

Zircon grains were using conventional heavy liquid and magnetic methods at Langfang Geoscience Exploration Technology Services Co., Ltd., Hebei Province, China. The zircon grains were mounted on epoxy resin discs that were ground and polished to a half-section, exposing the cores of the zircon grains.

Zircon cathodoluminescence (CL) images were obtained at the Langfang Geoscience Exploration Technology Services Co., Ltd., Hebei Province, China, to observe the internal textures of the crystals and select potential target sites. Zircon U-Pb dating and trace element analyses were analyzed using an Agilent 7 900 ICP-MS, coupled with a Resonetics RESOlution S-155 ArF 193-

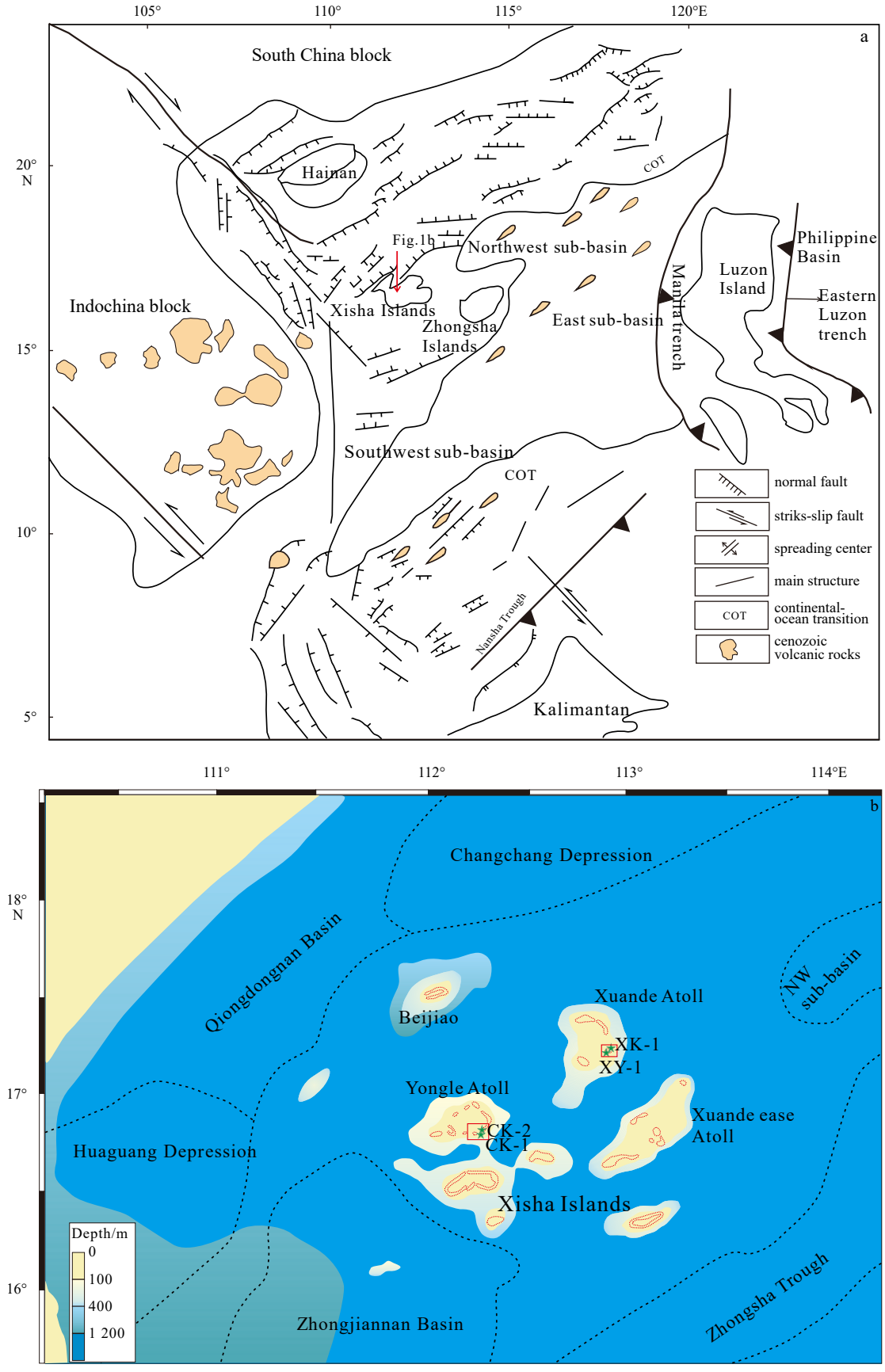

Fig. 1. Geological sketch of the SCS and its adjacent areas (a); location of Well CK-1 (b)(Zhang et al., 2018; Wang et al., 2018). The depth is below sea level and in meters.

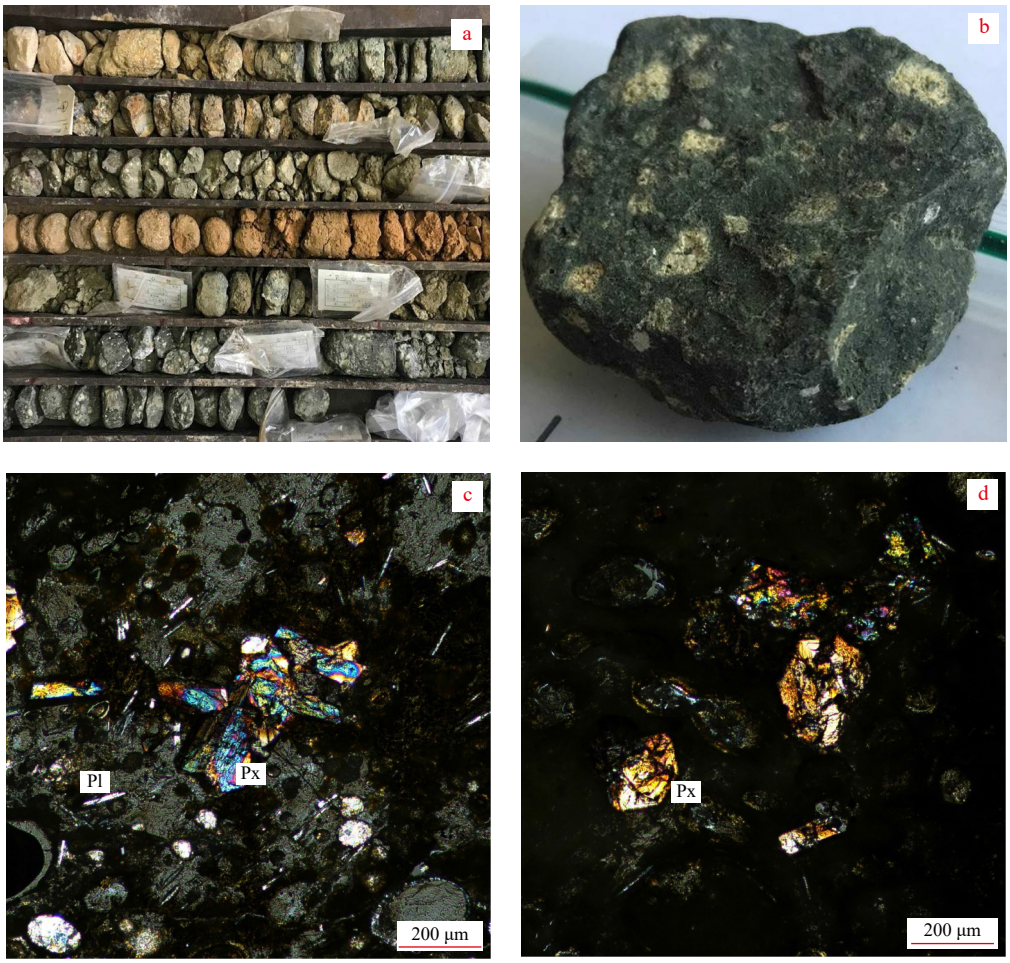

Fig. 2. Photographs of the basaltic pyroclastic rocks in hand specimen and under the microscope (cross polarized). Labels represent: Px-pyroxene; Pl: plagioclase.

nm laser ablation system (spot size of 29 μm, repetition frequency of 8 Hz, and ablation time of 40 s). Harvard 91 500 zircon (age = 1 064 Ma; Wiedenbeck et al., 1995) was used as an external standard for age calculations, and NIST SRM 610 glass was used as an external standard for U, Th, and Pb concentration calculations. Calculations of the zircon isotope ratios and zircon trace elements were performed using the ICPMS DataCal program (Liu et al., 2008, 2010). Concordia diagrams were constructed using ISOPLOT 3.23 V (Ludwig, 2003).

4 Analytical results

Total of twenty-five spots were analyzed on twenty-two zircon grains selected from the basaltic pyroclastic rock sample during this study. The LA-ICP-MS dating results are listed in Table 1. CL images of representative zircons are shown in Fig. 3. The zircon grains are generally euhedral and subhedral and 50–150 μm in length, with length-to-width ratios of 1:3. Oscillatory or blurry zoning was observed in CL images (Fig. 3). The zircon grains have variable Th (35×10^{-6}–760×10^{-6}) and U (49×10^{-6}–568×10^{-6}) concentrations, yielding Th/U ratios of 0.42–1.62 (Table 1), suggesting magmatic origins (Hanchar and Hoskin, 2003).

Most of the analysis points were plotted on or near the concordant curve in the $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$ concordia diagram (Fig. 4). The youngest and oldest ages were 36 Ma (CK01-D4-3) and 2 138.9 Ma (CK01–D5-2), respectively. Mesozoic ages were common in this sample (146.1–105.7 Ma, eight grains). The Neoproterozoic ages range from 884.1 Ma to 623.4 Ma (nine grains). In addition, there was one Paleozoic zircon grain (300.2 Ma, CK01–D4-2).

5 Discussions

5.1 *Basaltic pyroclastic rocks property*

Pyroclastic rocks are formed when the pyroclastic material from volcanic eruptions is transported, deposited, and consolidated with air or water (Sun et al., 2001; Zhou et al., 2022). It is a transitional-type rock between lava and sedimentary rocks (Sun et al., 2001). The basement of Well CK-1 was composed of basaltic pyroclastic rocks. We suggest that the basaltic pyroclastic rocks from Well CK-1 are pyroclastic rocks on the seamount, based on the following lines of evidence:

(1) The petrographic research results show that the composition of basaltic pyroclastic rocks is single, and there is an absence of terrigenous detritus within the pyroclastic rocks (e.g., quartz), which is consistent with the characteristics of pyroclastic rocks on seamounts (Yan and Shi, 2009; Fan et al., 2021a, 2021b). The pyroclastic rock on the seamount was a product of subaqueous explosive volcanism (Fouquet et al., 1998; Davis and Clague, 2006; Yan and Shi, 2009). If the depth of the magmatic eruption is greater than the pressure compensation depth, explosive volcanism can occur, producing volcaniclastic sediments. The positive topography at the top of the seamount limited the arrival of exo-

Table 1. LA-ICP-MS zircon U-Pb isotope data the basaltic pyroclastic rocks from Well CK-1

Sports	Th/ 10^{-6}	U/ 10^{-6}	Th/U	Isotopic ratios(1σ)						Apparent ages/Ma						Concordance
				$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	
CKO1-D1-1	401	247	1.62	0.075 3	0.001 8	1.187 0	0.037 0	0.113 4	0.001 8	1 075.9	47.4	794.6	17.2	692.7	10.6	86%
CKO1-D1-2	303	292	1.04	0.053 0	0.001 1	0.348 6	0.007 6	0.047 7	0.000 5	331.5	46.3	303.6	5.8	300.2	3.2	98%
CKO1-D2-1	283	312	0.91	0.065 5	0.000 7	1.197 3	0.017 8	0.132 2	0.001 4	790.7	24.1	799.4	8.2	800.2	8.1	99%
CKO1-D2-1-2	335	369	0.91	0.065 8	0.000 8	1.193 7	0.020 4	0.131 2	0.001 6	799.7	25.9	797.7	9.5	794.6	9.3	99%
CKO1-D2-2	203	257	0.79	0.063 7	0.000 8	1.148 2	0.017 8	0.130 4	0.001 3	731.5	27.8	776.4	8.4	789.9	7.5	98%
CKO1-D2-3	514	371	1.39	0.066 6	0.000 9	0.965 0	0.016 1	0.104 7	0.001 0	833.3	29.6	685.9	8.3	642.0	6.1	93%
CKO1-D3-1	191	302	0.63	0.050 4	0.001 5	0.120 8	0.003 7	0.017 4	0.000 2	216.7	70.4	115.8	3.3	111.1	1.3	95%
CKO1-D3-2	57	51	1.13	0.058 6	0.008 7	0.035 1	0.003 9	0.005 9	0.000 2	553.7	330.5	35.0	3.8	37.7	1.4	92%
CKO1-D3-3	65	155	0.42	0.066 6	0.001 1	1.352 9	0.023 5	0.147 0	0.001 4	833.3	33.3	868.8	10.1	884.1	7.7	98%
CKO1-D3-4	181	349	0.52	0.049 9	0.001 9	0.114 8	0.004 3	0.016 9	0.000 3	190.8	87.0	110.4	3.9	108.0	2.1	97%
CKO1-D4-1	84	113	0.74	0.066 4	0.001 2	1.188 6	0.022 0	0.129 9	0.001 3	818.2	32.4	795.3	10.2	787.4	7.7	98%
CKO1-D4-2	35	49	0.72	0.065 8	0.001 6	1.151 4	0.029 2	0.127 2	0.001 6	1 200.0	51.9	777.9	13.8	771.7	8.9	99%
CKO1-D4-3	459	539	0.85	0.047 1	0.002 8	0.036 1	0.002 0	0.005 6	0.000 1	57.5	133.3	36.0	2.0	36.0	0.6	99%
CKO1-D4-4	132	236	0.56	0.062 6	0.002 4	0.152 8	0.006 0	0.017 8	0.000 2	696.0	82.6	144.4	5.3	113.5	1.5	76%
CKO1-D5-1	250	265	0.94	0.051 6	0.001 9	0.124 0	0.005 0	0.017 4	0.000 3	333.4	83.3	118.7	4.5	111.0	1.7	93%
CKO1-D5-2	204	284	0.72	0.133 0	0.001 1	7.362 9	0.096 4	0.400 7	0.004 5	2 138.9	13.9	2 156.5	11.8	2 172.1	20.8	99%
CKO1-D6-1	133	112	1.19	0.070 5	0.001 6	1.242 9	0.028 5	0.127 8	0.001 3	942.6	46.3	820.2	12.9	775.4	7.6	94%
CKO1-D6-2	142	153	0.93	0.056 2	0.002 6	0.159 5	0.006 6	0.021 3	0.000 4	457.5	106.5	150.2	5.8	136.0	2.3	90%
CKO1-D6-3	255	215	1.19	0.053 9	0.002 2	0.170 2	0.007 3	0.022 9	0.000 3	368.6	92.6	159.6	6.3	146.1	1.7	91%
CKO1-D6-3-2	274	228	1.20	0.057 8	0.002 1	0.187 2	0.006 9	0.023 6	0.000 3	524.1	77.8	174.2	5.9	150.3	1.8	85%
CKO1-D6-5	237	281	0.85	0.067 8	0.006 4	0.196 1	0.019 5	0.020 9	0.000 3	864.8	199.1	181.8	16.5	133.6	1.7	69%
CKO1-D7-1	153	222	0.69	0.049 0	0.001 8	0.138 5	0.005 5	0.020 4	0.000 3	146.4	87.0	131.7	4.9	130.2	1.8	98%
CKO1-D7-2	760	568	1.34	0.066 8	0.000 9	0.937 1	0.014 5	0.101 5	0.001 1	831.5	25.9	671.4	7.6	623.4	6.7	92%
CKO1-D7-3	147	263	0.56	0.054 8	0.001 8	0.138 2	0.004 5	0.018 3	0.000 2	405.6	74.1	131.4	4.1	116.9	1.4	88%
CKO1-D7-3-3	119	222	0.53	0.048 2	0.002 2	0.109 9	0.005 0	0.016 5	0.000 2	109.4	107.4	105.9	4.5	105.7	1.4	99%

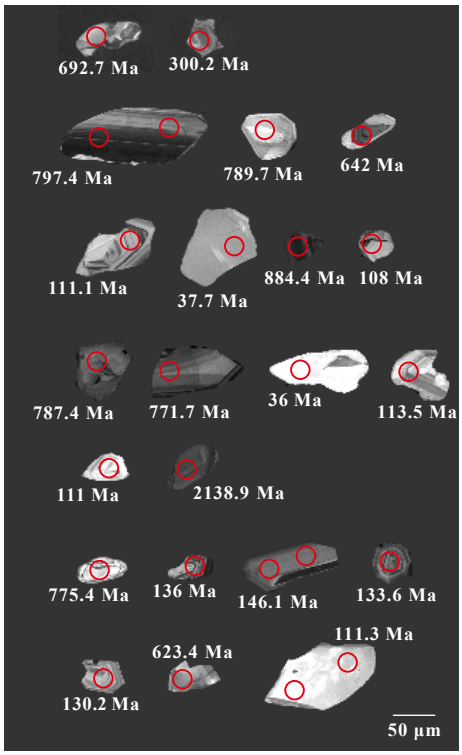

Fig. 3. CL images for U-Pb dated zircons for the basaltic pyroclastic rocks from Well CK-1.

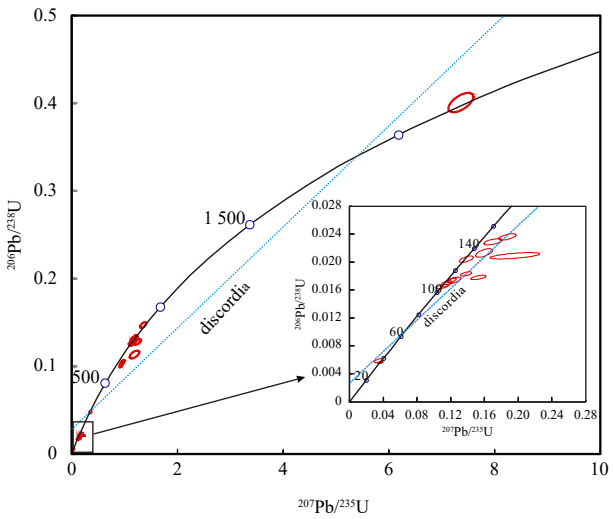

Fig. 4. Zircon U-Pb Concordia plots for the basaltic pyroclastic rocks from Well CK-1.

genous debris, making the composition of pyroclastic rocks on the seamount relatively singular, except for a small number of biological remains carried in a suspended manner (Yan and Shi, 2009). The size and quantity of biological remains are small compared to those of pyroclasts in pyroclastic rocks on seamounts (Zhang et al., 2014). Furthermore, the crystal clastic minerals are subangular or angular, mixed in size, and broken into steps or jagged shapes along the cleavage plane (Fig.2), suggesting that the basaltic pyroclastic rocks from Well CK-1 may have been deposited *in situ*.

(2) The thickness of the basaltic pyroclastic rocks from Chenhang Island is more than 52 m (Zhang et al., 2018, 2020b). If they were transported over long distances by air or water, they would

have been widely distributed on the Xisha Islands. However, Wells XY-1 and XK-1, which are adjacent to Well CK-2 (Fig.1), penetrated the thick coral reef limestone into the underlying metamorphic basement. Similar basaltic volcanic clastic rocks are not found in either well (Wells XY-1 and XK-1), indicating that the basaltic pyroclastic rocks were deposited *in situ*.

(3) Huang et al. (2011a, 2011b) installed temporary earthquake stations on Chenhang Island. Based on earthquake observations and the onshore-offshore seismic experiments, Huang et al. (2011a) suggested that the thickness of the Earth's crust reaches its maximum beneath Chenhang Island and gradually decreases outward. Huang et al. (2011b) used natural seismic data from Chenhang Island to simulate the crustal structure and found that the lower crust has a ductile rheological structure caused by the deep thermal activity of the mantle.

(4) The depocenter around the Xisha Uplift (Huaguang Depression, Qiongdongnan Basin, Zhongjiannan Basin, and Xisha Trough) prevents exotic pyroclastic material from being deposited in the adjacent areas of the Xisha Uplift (Fig. 1), which further indicates that the pyroclastic material could not be transported over long distances by water.

In summary, we suggest that the basaltic pyroclastic rocks from Well CK-1 are pyroclastic rocks of the seamount. Based on the geophysical data in the Xisha area and its adjacent areas, Zhang et al., identified flat-topped and conical-topped seamounts in the Xisha area. The flat-topped seamount is characterized by a flat and wide top, but a steep slope. Magnetic anomalies suggest that the flat-topped seamount may be basaltic in nature rather than continental crust or shallow-water sandstone deposits. The conical-topped seamounts are thought to have been formed by a strong central eruption of the volcano. In contrast to flat-topped seamounts, conical-topped seamounts have high and sharp heads exposed above the seafloor (Zhang et al., 2014, 2016). We further speculated that Chenhang Island may be one of the seamounts described by Zhang et al. (2014, 2016). After the Miocene, the Xisha Islands began to sink and were gradually submerged. Consequently, the area has suitable temperature, salinity and water depth, and coral reef strata have been extensively developed.

5.2 *The age of the basaltic volcanic clastic rocks*

Precise dating of basic volcanic rocks, particularly young basic volcanic rocks, is an important scientific problem that has long plagued geologists. Si and Zr are normally unsaturated in basic rocks. Zircons in basic volcanic rocks usually have multiple geneses, particularly in young samples. They may have crystallized in the magma reservoirs from which the rocks were derived or may have been trapped from the wall rock through which the magma was raised (Hanchar and Hoskin, 2003; Song and Qiao, 2008; Pereira et al., 2011). Volcanic eruption events are instantaneous during geologiccal evolution, and it is difficult to simultaneously form contemporaneous zircons with basaltic eruptions. Most zircon grains in basic volcanic rocks, especially larger zircon grains, are formed in the magma chamber or captured during the upward migration of magma through a conduit (Song and Qiao, 2008). If sufficient zircon grains are analyzed in volcanic rocks, the youngest ages among them would be nearest to the age of the volcanic eruption and could be regarded as a maximum estimation of the age of the volcanic eruption (Song and Qiao, 2008).

In this study, the youngest zircon ages were considered as the maximum ages of the basalt eruption. Two Cenozoic zircons from Well CK-1 gave a weighted mean $^{206}Pb/^{238}U$ age of 36.3 ± 1.1 Ma Mean Squared Weighted Deviation [(MSWD) = 1.2], which may represent the maximum age of the volcano eruption. Furthermore, there are eight Cenozoic zircon grains from Well CK-2, which gave a weighted mean $^{206}Pb/^{238}U$ age of (35.5 ± 0.9) Ma (Zhang et al., 2020b), which is consistent with our study within error. Therefore, we suggest that the age of the basaltic volcanic eruption beneath Chenhang Island was as early as 36 Ma.

5.3 *Basement nature of Xisha micro-block*

As discussed in Section 5.1, the basaltic pyroclastic rocks from Well CK-1 were pyroclastic rocks on the seamount. The older zircon grains from Well CK-1 were inherited zircons rather than being detrital zircons. Information obtained from inherited zircons is crucial for decrypting the time intervals of older magmatic events that are poorly exposed on the crustal surface. The inherited zircons can be used to indicate concealed magmatic events (Zheng et al., 2006; Condie et al., 2009; Pereira et al., 2011; Pan et al., 2014; Zhu et al., 2016; Wang et al., 2020).

The inherited zircons from Well CK-1 displayed three major age groups: 116.9–105.7 Ma, 146.1–130.2 Ma, and 884.1–623.4 Ma. Late Mesozoic Yanshanian igneous activity was widely dispersed in the SCS and its surrounding areas, such as the Nansha, Zhongsha, and Xisha micro-blocks, and Pearl River Mouth Basin (Jin, 1989; Li et al., 1999; Qiu et al., 2008; Yan et al., 2008a, 2010, 2014, Shi et al., 2011; Wang et al., 2015; Zhu et al., 2017 and references therein). It is generally accepted that these Late Mesozoic magmatic activities are related to the subduction of the Paleo-Pacific Plate beneath the Eurasian Plate (Zhou and Li, 2000; Li et al., 2007a, 2018; Li and Li, 2007; Chen et al., 2008; Shi et al., 2011; Yan et al., 2014; Xu et al., 2017; Yuan et al., 2018 and references therein).

The ages of the late Mesozoic Yanshanian igneous rocks from the SCS region range from 159 Ma to 70.5 Ma, indicating that the late Mesozoic igneous activity in the SCS lasted for a long time (Yan et al., 2014). The magmatic ages of the granitic rocks from the Nansha micro-block varied from 159 to 127 Ma, implying the existence of a continental basement within the Nansha micro-block (Yan et al., 2010). Fine-grained biotite granite was dredged from the southwestern SCS Basin. K-Ar, Ar-Ar, and U-Pb dating showed that these granites formed during the Early Cretaceous (120–109.7 Ma) (Qiu et al., 2008). In the northern SCS basin, many boreholes have been drilled into the basement metamorphic rocks (e.g., P1-1-1 and YJ35-1-1 from the Pearl River Mouth Basin; HK17-1-1 and HK30-3-1A from the Yinggehai Basin; WZ23-3-1, WS31-1-1, and WS26-4-1 from the Beibu Gulf Basin; and BD15-3-1 and YC13-4-1 from the Qiongdongnan Basin). However, owing to the lack of high-precision dating and stratigraphic sequences, it is not yet possible to distinguish whether they are Precambrian crystalline basements or late-stage tectonic metamorphisms (Sun et al., 2014). Jin (1989) identified biotite-plagioclase gneiss in the basement of the Zhongsha micro-block. The biotite and plagioclase from the metamorphic rocks yielded K-Ar ages of 127–119 Ma (Jin, 1989), which is consistent with Early Cretaceous igneous activity in southeastern China (Zhou and Li, 2000; Shi et al., 2011). Kudrass et al. (1986) reported the Jurassic–Cretaceous metamorphic rocks dredged from Reed Bank. The K-Ar ages of these samples were 146 Ma, 122 Ma, and 113 Ma for the amphibolite, paragneiss, and phyllite, respectively (Kudrass et al., 1986).

Well XK-1 is located 80 km from CK-1. Its basement comprised of Late Jurassic amphibole plagioclase gneiss (152.9 ± 1.7 Ma) and was intruded by late Early Cretaceous granitic magma [(107.8 ± 3.6) Ma] (Zhu et al, 2017). Based on the presence of contemporaneous metamorphic rocks in the SCS, Zhu et

al. (2017) suggested the presence of an E–W trending metamorphic zone within the northern SCS during the Cretaceous. The Late Mesozoic inherited zircons (116.9–105.7 Ma and 146.1–130.2 Ma) from Well CK-1 are consistent with the zircons from Well XK-1. There were two peak periods of Yanshanian igneous activity in southeastern China (195–150 Ma and 131–117 Ma) (Wu et al., 2005a, 2005b). Similar zircon ages indicate that late Mesozoic magmatism in the Xisha micro-block is consistent with that in southeastern China and imply that the northern SCS area may have a geodynamic setting similar to that of southeastern China during the Mesozoic. Combined with the zircon U-Pb ages from CK-2 (Fig. 5), we further speculate that the basement of Chenhang Island may be similar to that of Well XK-1. As the Cenozoic basaltic volcanic eruption on Chenhang Island, the Late Mesozoic zircons were preserved in the basaltic pyroclastic rocks in the form of inherited zircons. The Xisha micro-block may have developed on a uniform Late Jurassic metamorphic crystalline basement intruded by the Cretaceous granitic magma (Fig. 6).

Furthermore, several Neoproterozoic zircons were present in this study (884.1–623.4 Ma). A similar Neoproterozoic inherited zircon (675 Ma) was identified from the granitic rocks in the Nansha micro-block, which may have been produced by the partial melting of the older Precambrian basement (Yan et al., 2008b, 2010). The crustal remelting of the old Precambrian basement corresponds to the rapid thinning of the South China lithosphere during the Mesozoic, which covered the imprint of the Precambrian crystalline basement in the study area (Wan, 2004; Xu, 2008).

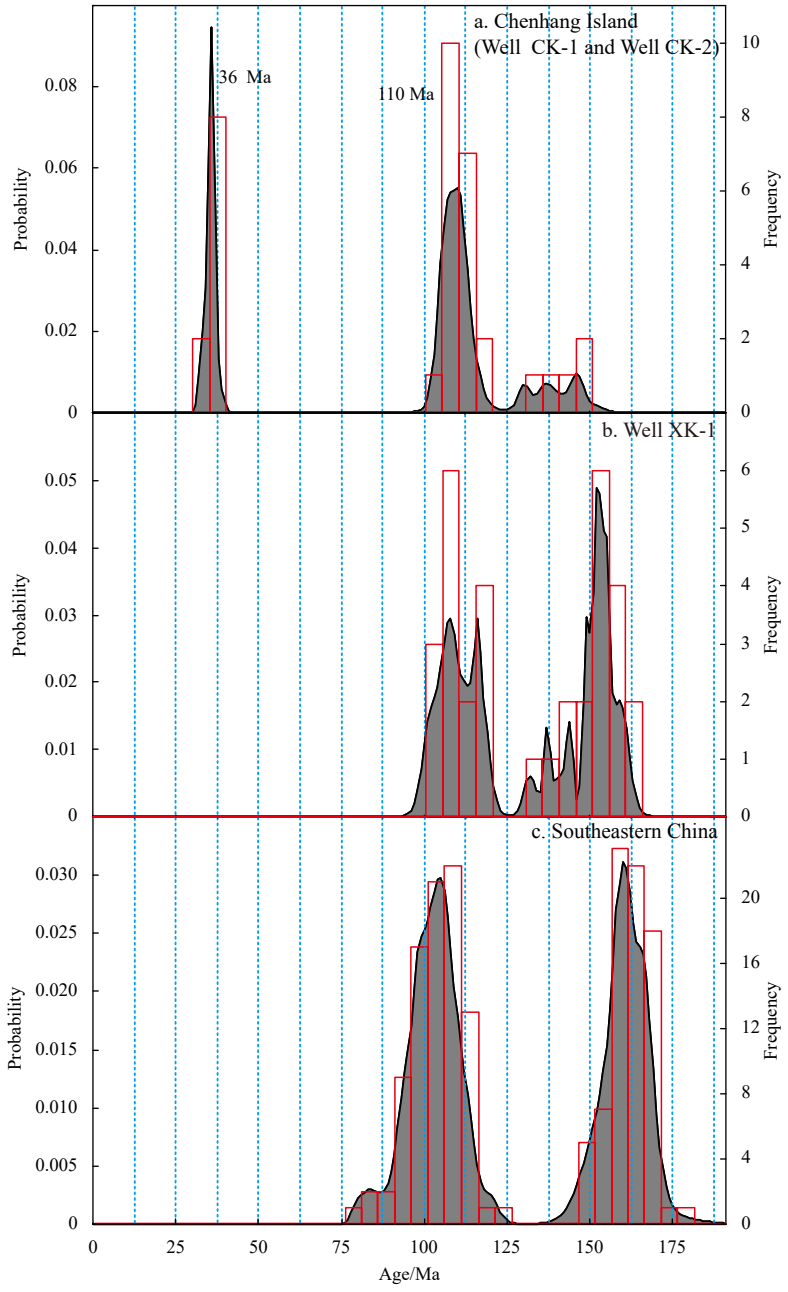

Fig. 5. Relative probability density diagram of ages for the analyzed samples along with complied plots from surrounding areas. a. Chenhang Island (Well CK-1 and Well CK-2). Data sources are Zhang et al. (2020b); b. Well XK-1. Data sources are Zhu et al. (2017). c. Southeastern China. Data sources are Li et al. (2007b) and Yuan et al. (2019).

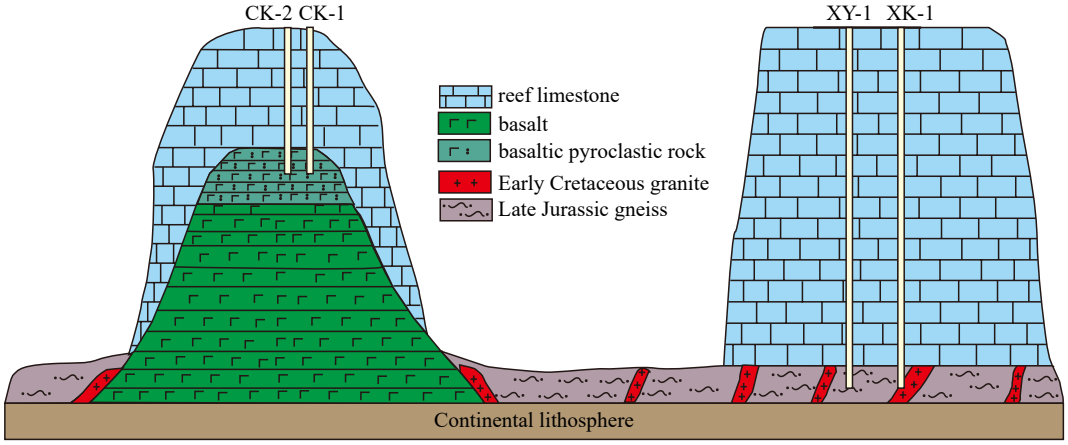

Fig. 6. Schematic diagram for the basement of Xisha Islands.

6 Conclusions

The basement of Well CK-1 consists of basaltic pyroclastic rocks on the seamount. LA-ICP-MS U-Pb dating showed that the basaltic volcanic eruption occurred as early as 36 Ma. The Xisha micro-block may have developed on a uniform Late Jurassic metamorphic crystalline basement intruded by the Cretaceous granitic magma.

Acknowledgements

We are grateful to two anonymous reviewers who provided constructive suggestions regarding an earlier version of the paper.

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