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Origin of the serpentinites in the Lichi mélange, eastern Taiwan, China: implication from petrology and geochronology

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ABSTRACT

Lichi mélange, located in the southern coastal range, eastern Taiwan, China, is a typical tectonic mélange of the plate’s boundary zone between the Eurasian Plate and the Philippine Sea Plate. It formed during the collision of the Luzon arc with the Eurasian Continent (arc-continent collision). It is composed of sandstone and/or mudstone matrix and many kinds and sizes of rock fragments, including some sedimentary rocks, volcanic rocks and a few metamorphic rocks. The serpentinite is one of the common fragments in the Lichi mélange. By the petrographic characteristics and the zircon U-Pb chronology analyses, protolith of the serpentinite is peridotite, the age is 17.7 ± 0.5 Ma. Taking the tectonic background into account, it is inferred that the serpentinite (serpentinised peridotite) come from the forearc basin (the North Luzon Trough) and was taken into the mélange by a second thrust westwards. The origin of the serpentinite in Lichi mélange is helpful to understand the formation of the Lichi mélange and can provide reliable detailed information for the study of the arc-continent collision orogenic activity in and offshore Taiwan.

1. Introduction

Taiwan is in the boundary zone between the Philippine Sea plate and the Eurasian plate, formed by the collision between the Luzon arc and the Eurasian continent (arc-continent collision). The Lichi mélange is located in the southern Coastal range, of eastern Taiwan, China (Fig. 1), which is affected by the Manila subduction zone. Many studies show that the Lichi mélange is formed due to an arc-continent collision. The arc-continent collision is active offshore southern Taiwan at present (Biq C, 1972; Bowin C, 1978; Suppe J, 1981; Ho CS, 1986; Teng LS, 1990; Huang CY and Yin CY, 1990; Chung SL and Sun SS, 1992; Huang CY et al., 1992, 1993, 1997, 2000, 2008; Reed DL et al., 1992; Liu CS et al., 1998; Malavieille J et al., 2002; Sibuet JC and Hsu SK, 2004; Geng W et al., 2013; Geng W et al., 2014, 2018). Therefore, the origin of the Lichi mélange is key to understanding the arc-continent collision. The Lichi mélange, typical tectonic mélange (Chang CP et al., 2000; Huang CY et al., 2000; Malavieille J et al., 2002; Huang CY et al., 2008), is located in a complex tectonic zone, where not only the suture belt of the Philippine Sea plate and the Eurasian plate, but also the crust-mantle interaction area. It is difficult to study the Lichi mélange because it is the result of multiple tectonic activities, characterized by unstratified, disordered distribution, mixing diverse lithological rocks, and a strong shear fracture.

The exotic fragments of different sizes in the Lichi mélange, including sedimentary rocks, volcanic rocks and a few metamorphic rocks. It is important to analyze the origins of the exotic fragments to understand the formation of the Lichi mélange, especially the serpentinite (serpentinizated peridotite), because peridotite is a dominant rock of the upper earth's mantle, so the serpenitite has a special tectonic significance for the formation of the Lichi mélange. It is an important means of understanding the deep lithosphere information in the manila subduct zone in studying the origin of the serpenitite in the Lichi mélange, and it is also the key point to clarify the interaction between the Philippine Sea plate and the Eurasian plate. It also provides a direct case

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study for the ongoing arc-continent collision offshore southern Taiwan.

Serpentinite is also called serpentinizated peridotite, all the peridotites on the seafloor are more or less serpentinized (Mével C, 2003; Wang XM et al., 2010). The peridotite provides samples of the Earth's mantle brought up from depths ranging from about 30 to 200 km or more. So, the serpentinite/peridotite provides clues to the early composition of the Earth's mantle and the complexities of geodynamics. The serpentinites in the Lichi mélange located in the critical zone of the arc-continental collision can provide important detailed information for studying the orogenesis of the arc-continent collision and deep lithosphere activities. We study the petrology and chronology of the serpentinite in the Lichi mélange in this paper, mainly to analyze the origin of the serpentinite and infer the genesis of the Lichi mélange in providing a reliable detailed geological basis for processing the arc-continent collision.

Taiwan and the southwards offshore area to the Philippines are all under the influence of the Manila subduction system since the Miocene when Taiwan’s orogeny began to form and remain active at present. The orogeny offshore Taiwan now are still in the arc-continent collision intensively under the sea southwards in stress of the Manila subduction system (Ho CS, 1986; Teng LS, 1990; Sibuet JC and Hsu SK, 2004; Fig. 1). The Lichi mélange is mainly distributed in the southern part of the Coastal Range and the east side of the Longitudinal Valley. The thickness of the Lichi mélange is unknown because the width of outcrop in the field can reach several thousand meters but no beddings (Chen CH, 1990).

The Lichi mélange is composed of thick layers of gray

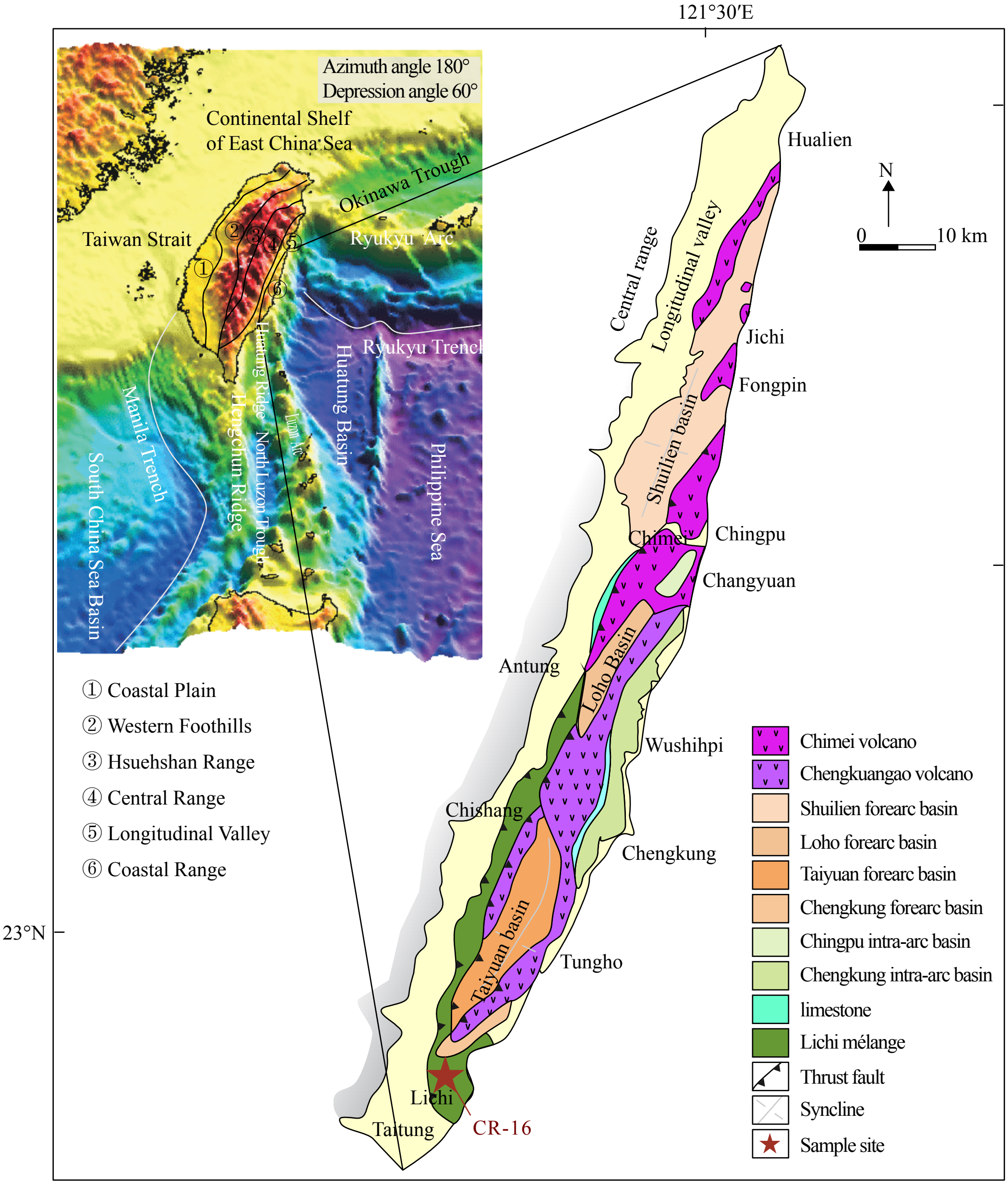

Fig. 1. Tectonostratigraphic map of the coastal range and location of sample CR-16 (modified from Huang CY et al., 2000).

loose siltstone and/or mudstone including many kinds and sizes of exotic rock fragments (Fig. 2a), which have already been sheared, abraded or inversed. These fragments are of all sizes, some are large to several meters even to several thousand meters in diameter, some are less than 1cm in diameter. The Lichi mélange consists of a jumble of large blocks of varied lithologies, such as serpentinite, andesite, gabbro, basalt, sandstone, siltstone, shale, mudstone, conglomerate, slate and limestone. Serpentinite is one of the common fragments, and the largest serpentinite fragment is about 3.5 km in diameter and exposed near Guanshan.

The strike of one lamellation of matrix siltstone and/or mudstone is NNE 0–30°, and the dip is eastwards 70°–90°. And another lamellation, occurred in the contact zone between the Lichi mélange and other normal strata or river terraces, the strike is NNE 20°–45°, and the dip is eastwards 50°–80°. There are often obvious scratches on the lamellation surface, indicating they have been subjected to a strong shear force. According to fossil data in the mudstone matrix of the Lichi mélange, it was formed in Pliocene (Chang LS, 1967; Huang TY, 1969; Chi WR et al., 1981; Chi, 1982; Barrier E and Muller C, 1984). The Lichi mélange and adjacent strata, Tuluanshan Formation, Fanshuliao Formation, Paliwan Formation, Penan Conglomerate or Quaternary terraces are unconformilty connect with faults (Fig.1).

2. Samples and experimental methods

Sample CR-16, a large piece of serpentinite over 5kg, which is most typical of rocks in the Lichi mélange, was collected from the Lichi mélange outcrop under the Lichi Brige in the Lichi village, Taitung (Fig.1; GPS: N22°48′36.6″, E121°08′17.6″, altitude: 61 m).

We first removed the surface dirt and eliminated non-relevant substances from the collected andesite and clastic rock samples. After mechanical crushing, coarse scouring (manual washing), strong magnetic sorting, electromagnetic sorting, heavy fluid separation, and high-frequency dielectric separation, we picked zircons that had no cracks or inclusions under the binocular microscope and attached them to double-sided tape. We then used colorless, transparent epoxy to affix the samples. After the epoxy had completely consolidated, we polished each sample until half of the zircon was exposed.

Cathode luminescence (CL) and secondary electron image analyses were conducted in the State Key Laboratory of Geological Processes and Mineral Resources (GPMR) of China University of Geosciences (Wuhan). To determine the internal structure of the zircon particles, we selected the test point of the zircon by avoiding zircon particles with cracks or dissolved pores. The region of the test point of the zircon needed to satisfy the following conditions: (1) no cracks or dissolved pores; (2) no inclusions; (3) no obvious radiative damage; (4) the diameter of the selected region was greater than 32 μm.

The U-Pb isotopic ages of the zircons were also analyzed using LA-ICP-MS in the State Key Laboratory of Geological Processes and Mineral Resources (GPMR) of China University of Geosciences (Wuhan). The laser ablation system is a GeoLas 2005, and the ICP-MS is an Agilent 7500a. A “wire” signal smoothing device is included in this laser ablation system, by which smooth signals are produced even at very low laser repetition rates down to 1 Hz. Helium was applied as a carrier gas. Argon was used as the make-up gas and mixed with the carrier gas via a T-connector before entering the ICP. Nitrogen was added into the central gas flow (Ar+He) of the Ar plasma to decrease the detection limit and improve precision (Hu ZC et al., 2008). Each analysis incorporated a background acquisition of approximately 20–30 s (gas blank) followed by 50 s of data acquisition from the sample. The Agilent Chemstation was utilized for the acquisition of each individual analysis. Off-line selection and integration of background and analyte signals, and time-drift correction and quantitative calibration for trace element analyses and U-Pb dating were performed by ICPMSDataCal (Liu YS et al., 2010). More detailed descriptions of the instrument operation and data processing methods are given by Liu YS et al. (2010).

The spot diameter was 32 μm. Zircon 91500 was used as an external standard to normalize isotopic discrimination during analysis. Concentrations of U, Th, Pb and trace

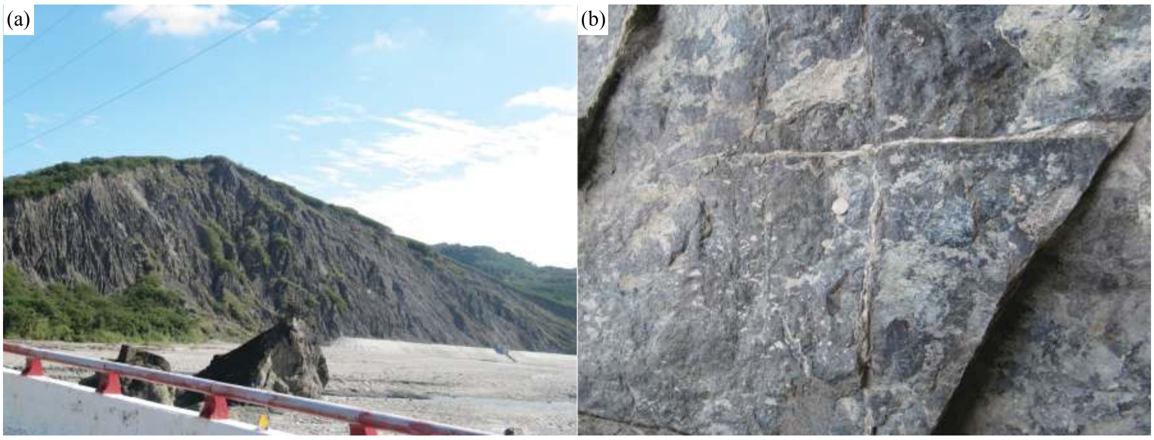

Fig. 2. The outcrop photo of the Lichi mélange (a) and the sample CR-16 in outcrop (b).

elements were calibrated using ^{29}Si as an internal standard and NIST 610 as an external reference standard. Uncertainties of individual analysis are reported with 1σ; weighted average ages are calculated at 2σ level. The age computation uses Isoplot 3 (Ludwig KR, 2003), and the isotopic age data are corrected using ComPbCorr#3-15. This paper selects the $^{206}Pb/^{238}U$ age as the zircon age for zircons with ages <1000 Ma.

3. Results

3.1. Petrological characteristics

Serpentinites of different sizes are widely distributed on outcrops in the field, most ranging from a few centimeters to 2 m in diameter. The serpentinite in the Lichi mélange appears alone without other ophiolites. Sample CR-16 is dark green with a blocky structure in appearance and is greasy looking and slippery feeling due to strong shears. Some of the serpentinites formed a network of carbonate veins, which are 1 mm to 2 cm in width (Fig. 2b).

Sample CR-16 microscopically shows mesh texture (Fig. 3a). The rim of the mesh consists of fibrous chrysotile and magnetite, and the inner part of the mesh is mainly small scaly antigorite showed white clouding positive relief in reflecting. The sample CR-16 still retains traces of peridotite crystal and precipitates many dust-like magnetite. The carbonate veins also commonly occur in microstructures. The mineral composition of sample CR-16 is antigorite (50%), chrysotile (35%), and magnetite (10%) and carbonate (5%) microscopically. It is inferred that the protolith of sample CR-16 is composed of olivine (95%) and pyroxenes (5%). It follows that the sample CR-16 was formed by intense serpentinization of peridotite (Fig. 3b), which can provide valuable information for the characteristics and evolution of the lithospheric mantle.

3.2. U-Pb age characteristics

The zircons from sample CR-16 range in size because they are badly broken, but most are between 50–100 μm (Fig. 4). The zircons of sample CR-16 are euhedral to subhedral, and show eroded pores, fractures and embayment-like edges due to hydrothermal erosion. Most zircons have larger aspect ratios and clear ring-belts in the CL images, which exhibit a typical core-mantle-margin structure. The Th/U ratios of these zircons range from 1.31–3.3 (all are greater than 0.4) (Wu YB and Zheng YF, 2004), and the content of Th and U show a good positive correlation. All these characteristics indicate that the zircons of CR-16 are typical magmatic zircons. The LA-ICPMS results for the zircon grains from CR-16 are given in Table 1. The ages are in Cenozoic, so $^{206}Pb/^{238}U$ ages are taken as the ages of these zircons. The concordant U-Pb ages can be got by the close ellipses in the U-Pb harmonic curve (Fig. 5). The ages are concentrated from 20.8–16.4 Ma (MSWD=2.3) and the weighted mean is 17.7±0.5 Ma, represented the formation age of the serpentinite sample CR-16.

4. Discussions

4.1. Origin of Serpentinite

The formation of the Lichi mélange is a key problem in analysing the arc-continent collision, therefore, the origin of oceanic crust fragments such as serpentinite (peridotite) in the Lichi mélange has always been the focus of controversy. Some scholars believe that the serpentinites in the Lichi mélange come from the ocean crust of the South China Sea (Biq C, 1972; Suppe J, 1981; Ho CS, 1986; Teng LS, 1990; Huang CY and Yin YC, 1990). It was mixed by subduction of the ocean crust of the South China Sea eastward along the Manila trench beneath the Philippine Sea Plate. The calcium planktonic foraminifera fossils in the red shale overlying serpentinites show an age of 15 Ma (Huang TC and Ting JS, 1097), which is closed to the end of the South China Sea spreading (about 17 Ma; Taylor B and Hayes DE, 1983). However, through the Marine geological survey of Taiwan and offshore Taiwan in the 1990s, division of tectonic units of Taiwan and offshore Taiwan have been very helpful in the formation of the Lichi mélange. The Central Range-Hengchun

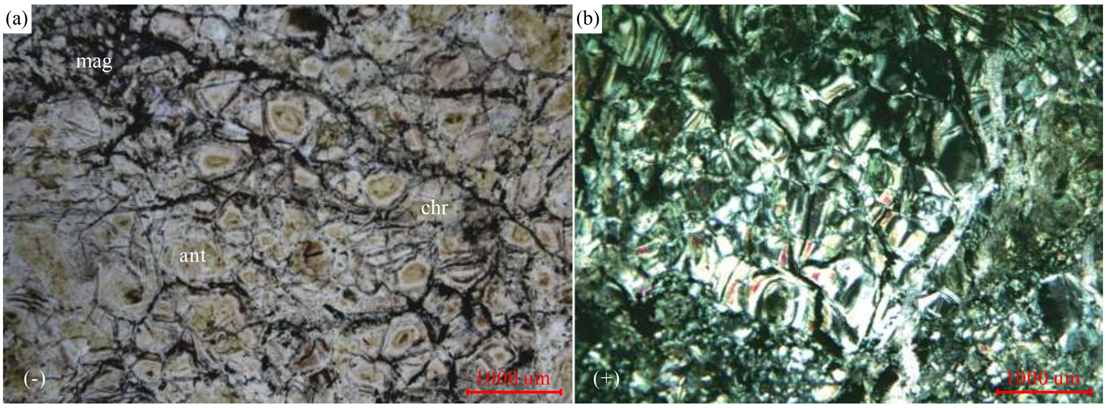

Fig. 3. Photomicrographs of serpentinite for Sample CR-16 in the Lichi mélange. ant– antigorite; chr–chrysotile; mag–magnetite. a–shows mesh texture, traces of peridotite crystal and many dust-like magnetite precipitated (plane polarized); b–shows intense serpentinization (crossed polarized).

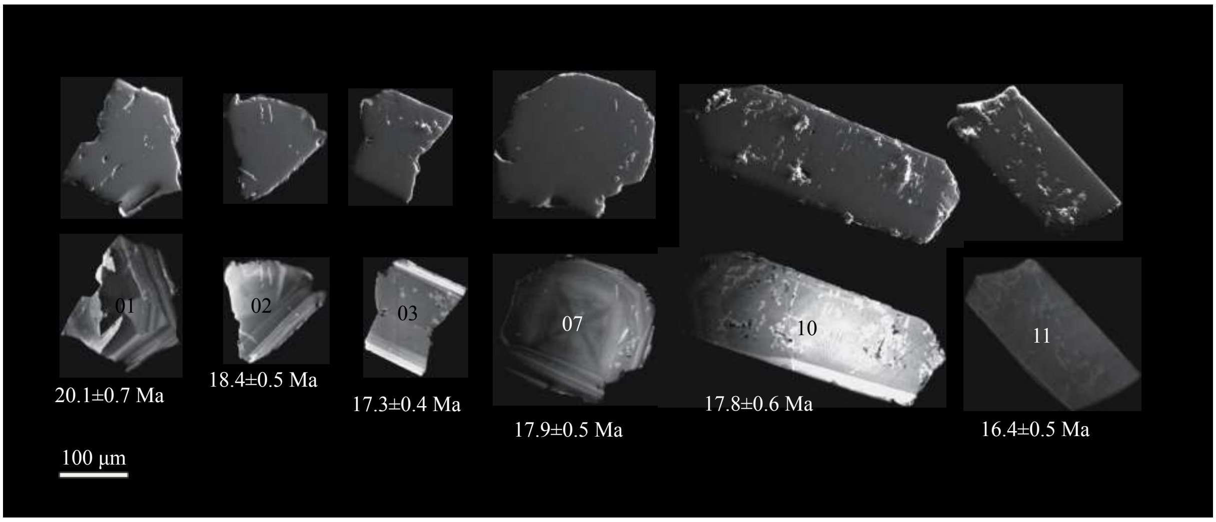

Fig. 4. Secondary electron images (above) and cathode luminescence (CL) images (below) of representative zircons from sample CR-16 in the Lichi mélange.

Table 1. U-Pb data for zircons from sample CR-16 in the Lichi mélange.

Point	$Th/10^{-6}$	$U/10^{-6}$	Th/U	$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		Rho	$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$	
				Ratio	1δ	Ratio	1δ		Age/Ma	1δ	Age/Ma	1δ
01	8713.87	2810.29	3.10	0.08143	0.00912	0.00313	0.00011	0.30	79.5	8.6	20.1	0.7
02	6466.59	2652.85	2.44	0.03275	0.00247	0.00285	0.00008	0.37	32.7	2.4	18.4	0.5
03	10575.96	3150.27	3.36	0.02600	0.00212	0.00268	0.00007	0.31	26.1	2.1	17.3	0.4
04	1591.10	1144.91	1.39	0.06552	0.00564	0.00284	0.00011	0.46	64.4	5.4	18.3	0.7
05	1359.32	1035.28	1.31	0.09187	0.00840	0.00323	0.00013	0.43	89.2	7.8	20.8	0.8
06	9256.35	2992.29	3.09	0.04407	0.00721	0.00266	0.00007	0.17	43.8	7.0	17.1	0.5
07	4670.87	2517.91	1.86	0.03789	0.00317	0.00278	0.00008	0.34	37.8	3.1	17.9	0.5
08	9487.53	3031.67	3.13	0.03393	0.00251	0.00269	0.00007	0.33	33.9	2.5	17.3	0.4
09	4713.09	2374.17	1.99	0.03777	0.00316	0.00286	0.00009	0.36	37.6	3.1	18.4	0.5
10	5198.71	2315.43	2.25	0.03536	0.00288	0.00276	0.00009	0.39	35.3	2.8	17.8	0.6
11	7263.84	2725.53	2.67	0.03079	0.00279	0.00254	0.00007	0.31	30.8	2.7	16.4	0.5
12	5054.18	2641.81	1.91	0.03590	0.00287	0.00271	0.00007	0.34	35.8	2.8	17.4	0.5
13	10001.42	3030.82	3.30	0.03132	0.00217	0.00264	0.00007	0.40	31.3	2.1	17.0	0.5
14	9479.40	2983.29	3.18	0.02505	0.00163	0.00272	0.00008	0.44	25.1	1.6	17.5	0.5
15	7965.91	2853.24	2.79	0.02792	0.00175	0.00272	0.00007	0.41	28.0	1.7	17.5	0.5
16	6253.29	2158.81	2.90	0.04646	0.00332	0.00320	0.00016	0.68	46.1	3.2	20.6	1.0
18	2548.62	1318.04	1.93	0.06640	0.00725	0.00271	0.00011	0.37	65.3	6.9	17.4	0.7
19	4872.20	2505.01	1.94	0.03388	0.00259	0.00273	0.00008	0.39	33.8	2.5	17.6	0.5
20	2341.44	1263.88	1.85	0.05901	0.00809	0.00257	0.00012	0.34	58.2	7.8	16.6	0.8

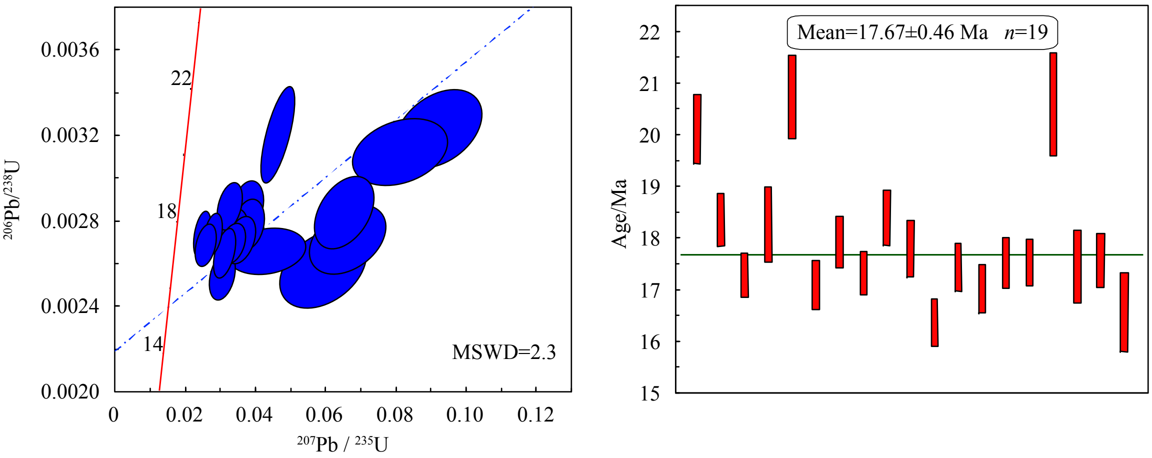

Fig. 5. U-Pb harmonic curves of zircons from sample CR-16 in the Lichi mélange.

Peninsula are an accretionary prism of the Manila subduction zone uplifted after the arc-continent collision. Furthermore, serpentinites are also found just in the Kenting mélange at the westernmost part of the Hengchun Peninsula, which is closer to the South China Sea. It suggests that serpentinites in the Lichi mélange might not be from the South China Sea. Zircons from gabbro in the Kenting mélange have been dated as 25.46±0.18 Ma, which together with geochemical data constrains the source to the South China Sea oceanic lithosphere (Zhang XC et al., 2016). Therefore, we are in agreement that it is more reasonable to take the serpentinites in the Hengchun Peninsula as the peridotites from the south China sea (Chu HT et al., 1988; Huang CY et al., 1997).

Other researchers have suggested serpentinites in the Lichi mélange come from the crust of the Philippine Sea (Juan VC et al., 1992; Malavieille J et al., 2002), which were taken by the subduction of the Philippine Sea beneath the Luzon forearc basin or the basement of the Luzon Arc. Mallavieille J et al. (2002) suggested that these serpentinites were mixed by the Philippine Sea Plate last subducting westwards at 1 Ma. This view may be more consistent with regional tectonics, but due to the lack of deep seismic data near the Luzon Arc/forearc basin, this view can only be used as one of the explanations of the origin of the serpentinites in the Lichi mélange. Some studies have shown that the spreading of the western Philippine Basin began at 55 Ma and ended at 33 Ma or 30 Ma (Deschamps A and Lallemand S, 2002). Some researchers have proposed the age of the Huatung Basin nearby the Coastal Range is earlier than the western Philippine Basin, probably early Cretaceous. Deschamps A et al. (2002) have dated a dredged sample of gabbro from the Huatung Basin is 121 –116 Ma. Yeh KY and Cheng YN (2001) have found early Cretaceous (115 Ma) radiolarians in Miocene to late pleistocene andesite breccia on Lanhsu volcanic island, a part of Luzon Arc in the south of the Coastal Range. All the data indicate that serpentinites in the Lichi mélange are less likely from the Philippine Sea.

Huang CY et al. (2008) have implied that the basic-ultrabasic fragments in the Lichi mélange are the materials of the basement of forearc basin, which have been mixed by backthrusting during the arc-continent collision process, just as peridotites formed in the Mariana Forearc Basin (Fryer P et al., 1985; Maekawa H et al., 2001; Huang CY et al., 2008). Many studies have reported that some serpentinites come from forearc basins, such as east Ladakh in northwest Himalayas (Guollot S et al., 2000), SE Anatolia in Turkey (Rizeli ME et al., 2016), the Eastern Desert in Egypt (Abdel-Karim AM et al., 2016) and the Oeyama forearc basin in Japan (Nozaka T, 2014). These peridotites were all formed in the process of mantle ultrabasic rocks reentry in the forearc basin. The oceanic crust of the South China Sea immediately began to subduct under the Philippine Sea plate after spreading ceased (32 –17 Ma) (Taylor B and Hayes DE, 1983). So the age of the forearc basin in the Manila subduction system should also be about 17 Ma. From all of the above tectonic background analyses, it is more reasonable to interpret the serpentinites in the Lichi mélange as coming from the forearc basin in the Manila subduction system.

4.2. Formation of the Lichi mélange

The North Luzon Trough is the forearc basin in the Manila subduction system, which is about 50 km wide, N-S trend and located in the south of the Coastal Range between the accretionary prism (Hengchun Peninsula-Hengchun Ridge) and the Luzon Arc (Fig. 1). The Northern Luzon Trough has been deeply affected by the arc-continent collision, and there is no obvious stratigraphic deformation in the forearc basin strata during the subduction. This is proven by the pelagic facies ’ strata in the southern part of the Northern Luzon Trough with little or no deformation at present (Reed DL et al., 1992; Huang CY et al., 1992; 2000; 2008). When the northern part of the forearc basin entered the initial stage of the arc-continent collision (Huang CY et al., 2006), the Luzon Arc stopped volcanic activities and began to collide with the Eurasia continent margin, and the western part of the basin experienced arcward backthrust (eastward thrust), forming the Huatung Ridge (Huang CY et al., 2008). The Huatung Ridge is the southern prolongation of the Lichi mélange in Coastal Range. When entering the advanced stage of the arc-continent collision, the Coastal Range uplifted during the forearc basin and a volcanic arc thrusting westward, the strata of Huatung Ridge thrust again (westward thrust), the fragments from the accretionary prism, volcanic arc and forearc basin mixed in the Huatung Ridge simultaneously.

Based on the analyses of the formation process of the Lichi mélange, because the first thrust is smaller in deformation degree and scale than the second thrust, thrust faults are probably not deep enough to reach the basement of the forearc basin, it is inferred that the serpentinites (serpentinized peridotites) should have been mixed in the

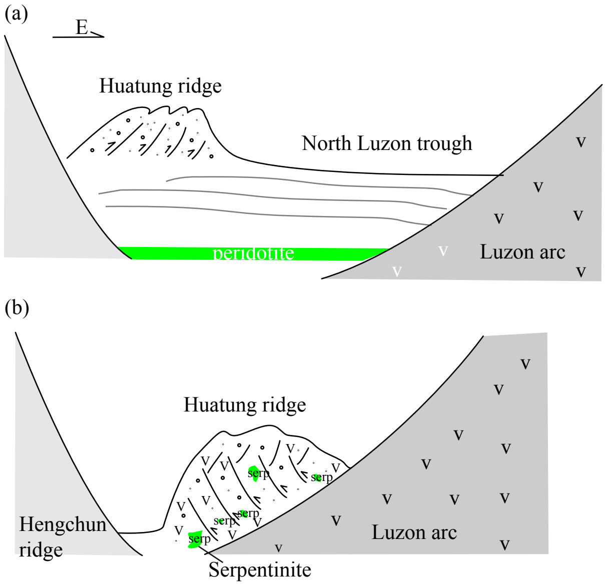

Fig. 6. Sketch of the serpentinites taken into the Lichi mélange by overthrusting in forearc basin. a−first thrust, eastwards; b−second thrust, westwards.

Lichi mélange during the westward thrust (Fig. 6). The westward thrust made the forearc basin deformation and uplift, then formed the Lichi mélange in the Coastal Range.

5. Conclusions

Based on the petrological and chronological characteristics of the serpentinite fragments in the Lichi mélange, considering the tectonic background, this paper provides detailed information about the process of the arc-continent collision, and draws the following conclusions:

(i) The protolith of the serpentinite in Lichi Mélange is peridotite, which can provide deep lithosphere information.

(ii) The formation age of peridotite was 17.7 ± 0.5 Ma.

(iii) Taking into account the age and evolution of the surrounding tectonic units, the serpentinites in the Lichi mélange are from the basement of the forearc basin of the manila subduction system.

(iv) The serpentinite (serpentinized peridotite), the basement of the forearc basin, was mixed in the process of the second thrust (westward) with the Luzon Arc and the forearc basin in the advanced arc-continent collision.

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