Abstract: The Susong metamorphic complex (SSC) in the southern margin of the Dabie orogenic belt (DOB) in central-eastern China is a key metamorphic unit for understanding subduction and exhumation processes in the DOB. However, the formation age and metamorphic grade of the SSC remain uncertain, hampering our understanding of the mechanism of the formation of the DOB. An integrated study of field survey, regional metamorphic petrology, geothermobarometry, and U–Pb dating of zircon was carried out in this study. Our results reveal that the SSC was metamorphosed under epidote amphibolite- to amphibolite-facies conditions with average metamorphic P–T values of 0.98 ± 0.07 GPa and 531 ± 35 °C. The smooth spatial variation in peak P–T conditions and an apparent geothermal gradient of ~17 °C/km indicate that the SSC as a whole fall into Barrovian-type metamorphic environments. Zircon U–Pb dating for garnet–mica schists of sample ZT003, ZT005 and ZT006 yield five (Groups I to V), six (Groups I to VI) and five (Groups I to V) age groups, respectively, concentrating on the Meso-Neoarchean, early-middle Paleoproterozoic, middle Mesoproterozoic, early Neoproterozoic, Palaeozoic and Triassic-lower Jurassic. Therein, a 259–190 Ma (Group V) from zircons with Th/U ratios of <0.1 in sample ZT006 record the timing of both peak and retrograde metamorphism for the SSC. All other ages are detrital zircon ages, and from age provenances in the DOB or the Yangtze Block (YZB), indicating the YZB affinity of the SSC. The two youngest age populations of 427–415 Ma (Group VI) and 475–418 Ma (Group V) from samples ZT005 and ZT006, respectively, suggest that the formation age of the SSC could be Middle Devonian. The similarity of formation age and peak P–T conditions of the SSC to Foziling Group, located in the northernmost DOB, implies that both units formed the sedimentary cover on the passive continental margin of the YZB during the late Palaeozoic, and subducted into the middle-lower crust of 20–40 km depth as a whole, corresponding to the shallow subduction. Compared to the deep subduction defined by high-pressure (HP) and ultrahigh-pressure (UHP) units, larger differences in peak P–T conditions, age and geothermal gradient between two different tectonic environments happen. Accordingly, it is speculated that a transitional subduction from shallow to deep levels occurred at Moho depths during the Early Triassic, and is due to a change in subduction dip angle.

Keywords: Susong metamorphic complex; peak metamorphic P–T conditions; U–Pb zircon ages; Late Palaeozoic sedimentary cover; Dabie orogenic belt

1. Introduction

The formation mechanism of deep continental subduction recorded by high-pressure (HP) and ultrahigh-pressure (UHP) rocks in the Dabie orogenic belt (DOB) in central-eastern China has received considerable attention [1–6]. However, investigations of subduction at crustal levels and the transition from shallow to deep subduction are scarce, which
restricts our understanding of the dynamic origin of the DOB. The DOB consists of the Beihuaiyang metamorphic belt (BHYMB), the North Dabie metamorphic belt (NDMB), the Middle Dabie metamorphic belt (MDMB), the South Dabie metamorphic belt (SDMB), the Susong metamorphic complex (SSC), and the Dabie complex (DBC; Figure 1) [2,7]. The SSC is located in the southern margin of the DOB [7–13] and shows tectonic affinity to the Yangtze Block (YZB). The SSC, composed of a set of metamorphic supracrustal rocks, is a key syntaxis between HP–UHP metamorphic units and a foreland fold-and-thrust belt across the DOB (Figure 1). As such, the SSC may provide insights into shallow subduction and the transition from shallow to deep subduction of the DOB. Unfortunately, the tectonic evolution of the SSC is still unclear, and the SSC is simply classified into the HP unit [1–3,5] according to insufficient petrological analysis [9–15]. Up to now, the metamorphic grade and timing of formation of the SSC remain ambiguous. Three possibilities have been proposed for the metamorphic conditions of the SSC: (1) upper green-schist facies metamorphism [8]; (2) blueschist to eclogite facies metamorphism [1–3,9–15]; and (3) epidote-amphibolite facies metamorphism [16–19]. These differing viewpoints imply that the depth of the subduction of the SSC is uncertain.

Figure 1. Simplified geological map of the southern margin of the Dabie orogen. Line A–B–C = geological profile; Yellow stars = sample sites for zircon geochronology. Inset: BHYMB = Beihuaiyang metamorphic belt; NDMB = north Dabie metamorphic belt; CDMA = central Dabie metamorphic belt; SDMB = south Dabie metamorphic belt; SSC = Susong Complex; DBC = Dabie Complex; ① = Xiaotian–Mozitan fault; ② = Shuihou–Wuhe fault; ③ = Hualiangtiang fault; ④ = Taihu–Mamiao fault; SMF = ShangMa fault; and TLF = TanLu fault.
As regards the SSC formation age, late Paleoproterozoic [8,20] and Palaeozoic [19,21] ages have been proposed, respectively. If the former, the SSC could be from the YZB [8,20]. If the latter, the similarity of Palaeozoic age for the SSC to that of the Foziling Group in the BHYMB in the northern margin of the DOB has been suggested (inset in Figure 1), and implies that both have the same tectonic process and genesis. However, if taking into account two controversial models: ① ‘independent micro-continent’ [22–25] and ② ‘accretionary wedge’ [1,7,26] for the formation of the Foziling Group, no model is suitable to account for the formation mechanism of the SSC, because the affinity to the YZB [1–3,7] of the SSC refute model ①, and model ② could not be supported by the uncertain metamorphic grade of the SSC [1–3,8–19]. Obviously, determining the peak P–T conditions and the formation age for the SSC is pivotal for probing into the tectonic evolution in the south of the DOB. In this study, detailed field surveys, regional metamorphic petrological investigations, thermodynamic evaluations, and zircon geochronological analyses were carried out. At the same time, the metamorphic grade and type, the spatial pattern of peak P–T conditions and formation age for the SSC were analysed in detail, and the transitional subduction from shallow to deep levels and its genesis is discussed.

2. Geological Setting and Samples
2.1. Geological Setting

From north to south, the DOB can be divided into the BHYMB, NDMB, MDMB, SDMB, SSC, and DBC [2,7,27–29]. These units are separated by the Xiaotian–Moizitan, Shuihou–Wuhe, Hualiangling, and Taihu–Mamiao faults, respectively. Geological setting: The BHYMB comprises the Foziling, Luzhenguan, and Meishan groups. The Foziling Group consists mainly of schist and marble [30–32], which was once considered as a non-metamorphosed to weakly metamorphosed flysch sediment [8,33–35]. The Luzhenguan Group is composed of granitic gneiss and plagioclase amphibolite [27,32,36–38]. The Meishan Group comprises sandstone, limestone, and a small quantity of slate and phyllite [8]. The NDMB contains migmatite, granitic gneiss, small amounts of metabasic and ultrabasic rocks, granulite, marble, and diamond-bearing eclogite [2,27–29,37,39–43]. The MDMB is composed of granitic gneiss, coesite- or diamond-bearing eclogite, epidote–biotite–plagioclase gneiss, marble, and small amounts of schist, jadeite, and quartzite [27,44,45]. The SDMB comprises granite gneiss, quartz eclogite, and schist [27,44–47]. The SSC consists of schist, granitic gneiss, and meta-basic rocks [8,18,19,27], and the DBC is composed of granitic gneiss and meta-basic rocks [28,29,48].

The study area, located in the southern margin of the DOB, contains the SDMB, the SSC, the Zhangbaling Group (ZBLG), Cenozoic–Palaeozoic sedimentary rocks, Mesozoic granites, and ultramafic rocks (Figure 1). The SSC occupies the main part of the study area. The SDMB and the ZBLG are situated in the northern and eastern parts of the study area, respectively, and they are separated from the SSC by the Liulin–Quanyueling and Talu faults, respectively (Figure 1). The SSC contains mainly schist, granitic gneiss, marble, and minor plagioclase amphibolite and quartzite, and develops a S–SSW-dipping foliation and a S–SE-trending mineral lineation (Figure 1). The schist is exposed between Chenhan–Beiyu–Liangteng–Erlangzhen and Liuling–Queyuelin (Figure 1), and can be further subdivided into mica, garnet–mica, and kyanite-bearing schists (Figure 2a–c). Centimetre-sized euhedral garnets are commonly observed at outcrops (Figure 2c). Garnet–plagioclase amphibolite typically crops out as 1–10 m lenses in the schist (Figure 2a,b). Marble is distributed predominantly between Luohanjian–Liuping and Erlangzhen–Beiyu and is in conformable contact with the schist (Figure 2d). The granitic gneiss can be divided into Palaeoproterozoic (~2.0 Ga) [20] and Neoproterozoic (0.77–0.83 Ga) [49] gneisses according to zircon U–Pb ages. The Palaeoproterozoic gneiss occurs in the Luohanjian–Liuping–Tingqian areas and contains Palaeoproterozoic basic dikes [20] (Figure 1). The Neoproterozoic gneiss is exposed across the SSC and interlayered with the schist (Figure 2e) [49]. In addition, Mesoproterozoic plagioclase amphibolite (~1.38 Ga) [50] with a width of ~200 m has been identified between Beiyu and Liulin and is juxtaposed against the schist (Figure 1).
The ZBLG, which is exposed east of the Tingqian–Erlangzhen–Liangting areas, consists mainly of felsic mylonite with a SE-dipping foliation and NE-trending mineral lineation (Figures 1 and 2f).

Figure 2. Field photographs of the SSC and ZBLG. (a–c) Lenses of garnet–mica schist and garnet–amphibolite (SSC); (d) thick-layered dolomitic marble (SSC); (e) granitic gneiss and mica schist occurring as a monocline (SSC); (f) felsic mylonite (ZBLG).

2.2. Petrography of Samples from the SSC

During this study, 157 samples were collected, mainly comprising schists, gneisses, marbles and garnet-plagioclase amphibolites from the SSC, with some felsic mylonites from the ZBLG.

The garnet–mica schist contains garnet (10–15 vol%), plagioclase (5–10 vol%), muscovite (20–25 vol%), biotite (10–15 vol%), quartz (25–30 vol%), dolomite (1–3 vol%), epidote (3–5 vol%), and rutile (1–3 vol%) (Figure 3a,b). Garnet grains range from 1 to 10 mm in diameter, have a euhedral or subhedral morphology, and contain abundant inclusions of rutile, epidote, and quartz. Plagioclase occurs as anhedral or subhedral grains with sizes of 0.1–2.0 mm. Muscovite and biotite both form euhedral or subhedral grains, with sizes ranging from 0.3 to 2 mm and 0.1 to 2 mm, respectively. Quartz occurs as anhedral grains measuring 0.1 to 1.5 mm. Dolomite is subhedral and ranges in size from 0.3 to 0.8 mm. Epidote is fined grained with sizes of 0.1–0.3 mm. Rutile occurs as anhedral grains measuring 0.05–0.2 mm in diameter, and grains are commonly surrounded by thin rims of ilmenite.
Figure 3. Photomicrographs showing the mineral assemblages of selected rock samples from the SSC and the ZBLG. (a, b) Garnet–mica schist with inclusions in garnet (sample TS060, SSC, plane-polarized light); (c, d) mica schist (sample MQ025, SSC, plane-polarized light) and kyanite-bearing schist (sample SS039, SSC, cross-polarized light), respectively; (e) garnet-plagioclase amphibolite with 'snowball' fabric (sample TS074, SSC, plane-polarized light); (f) granitic gneiss (sample TS050, SSC, cross-polarized light); (g) dolomitic marble (sample TS026, SSC, cross-polarized light); and (h) felsic mylonite showing ductile deformation (sample SS035, ZBLG, cross-polarized light).
The mica schist is composed of muscovite (30–35 vol%), quartz (50–55 vol%), plagioclase (5–10 vol%), rutile (<1 vol%), and tourmaline (<1 vol%) (Figure 3c). Muscovite forms euhedral grains measuring 0.3–2 mm in size. Quartz occurs as coarse grains ranging in size from 0.5 to 2 mm. Plagioclase grains are anhedral and have sizes of 0.1–0.3 mm. Rutile and tourmaline are fine-grained, with sizes of <0.1 mm.

The kyanite-bearing schist contains kyanite (3–8 vol%), quartz (40–45 vol%), muscovite (25–30 vol%), plagioclase (10–15 vol%), and epidote (3–5 vol%) (Figure 3d) and has previously been referred to as the UHP ‘white schist’ [11,12]. Kyanite forms anhedral grains of 0.2–0.4 mm in size. Quartz is anhedral, with grains measuring 0.1–0.8 mm in diameter. Euhedral or subhedral muscovite grains range from 0.3 to 1 mm in size. Plagioclase ranges from 0.2 to 0.6 mm in size and has anhedral morphology. Epidote occurs as subhedral grains measuring 0.1–0.5 mm in size.

The garnet–plagioclase amphibolite contains garnet (10–15 vol%), hornblende (30–35 vol%), plagioclase (20–25 vol%), quartz (15–20 vol%), biotite (3–5 vol%), epidote (3–5 vol%), and rutile (<1 vol%) (Figure 3e). Garnet occurs as subhedral or anhedral grains ranging from 0.5 to 5 mm in diameter. Epidote, quartz, amphibole, and rutile occur as inclusions in garnet and form a ‘snowball’ fabric. Garnets are typically surrounded by epidote + amphibole + plagioclase + quartz (Figure 3e). Amphibole in the matrix occurs as subhedral grains measuring 0.3–2 mm. Plagioclase is anhedral and ranges from 0.1 to 2.5 mm in size. Quartz forms anhedral grains with sizes of 0.1–2 mm. Biotite and epidote occur as euhedral grains that range in diameter from 0.1 to 0.5 mm and from 0.1 to 0.3 mm, respectively. Rutile occurs as anhedral grains measuring 0.1–0.3 mm.

The granitic gneiss has a granoblastic texture and comprises albite (20–25 vol%), microcline (30–35 vol%), quartz (30–35 vol%), and muscovite (3–5 vol%) (Figure 3f). Albite occurs as anhedral grains with sizes of 0.2–0.8 mm. Microcline occurs as anhedral to subhedral grains ranging in size from 0.1 to 0.5 mm. Quartz forms anhedral grains measuring 0.1 to 1 mm. Muscovite occurs as fine grains with sizes of 0.1–0.4 mm.

The dolomitic marble is composed predominantly of dolomite (>95 vol%) with subordinate muscovite (1–3 vol%) (Figure 3g). Dolomite occurs as subhedral grains measuring 0.1–0.2 mm. Muscovite with euhedral morphology varies from 0.1 to 0.3 mm in size.

The felsic mylonite in the ZBLG has mylonitic structure and consists of plagioclase (20–25 vol%), quartz (45–50 vol%), and muscovite (25–30 vol%) (Figure 3h). Plagioclase occurs as porphyroblasts with sizes of 0.5–2 mm and is surrounded by subgranular quartz measuring ~0.1 mm. Muscovite forms subhedral grains that range from 0.3 to 1 mm in size.

3. Analytical Methods

Mineral chemical analyses were conducted using a JEOL JXA-8230 electron microprobe at the EPMA laboratory of Hefei University of Technology, Hefei, China. Standard samples used during the period of analysis were in accordance with the specifications of the SPI 53 mineral standard and GB/T 17359-1998. Operating conditions included an accelerating voltage of 15 kV, a beam current of 8–20 nA, and a spot diameter of 3 µm. Counting times were 10 s at peak and 5 s at background positions. Detection limits (1σ) were in the range of 0.008–0.02 wt%. The ZAF correction process was applied to all data. The analytical conditions for garnet X-ray mapping included an accelerating voltage of 15 kV, a probe current of 40 nA, and a beam size of 3 µm. The structural formulae for garnet, plagioclase, and mica were calculated on the basis of 12, 8, and 11 oxygens, respectively. Ferric iron was calculated by charge balance for garnet.

Zircons were separated using standard magnetic and heavy-liquid techniques before handpicking under a binocular microscope. Cathodoluminescence (CL) images of zircons were obtained using a CL spectrometer (JEOL XM-Z09013TPCL) in the Scanning Electron Microscope Laboratory (SEM) of Hefei University of Technology. Zircon U–Pb dating analyses were performed by laser-ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) at the University of Science and Technology of China, using an ArF excimer laser system (GeoLas Pro, 193 nm wavelength) and a quadrupole ICP–MS instrument.
Analyses were performed using a pulse rate of 10 Hz, a beam energy of 10 J/cm², and a spot diameter of 32 µm. Each analysis consisted of ~60 s of sample measurement and ~30 s of background. Additional details regarding the U–Pb analytical techniques adopted in this study are reported in Hou [51]. Standard zircon 91500 was analysed to calibrate the mass discrimination and elemental fractionation, and U/Pb ratios were processed using the macro Excel program LaDating@Zrn. Common Pb was corrected using ComPb corr#3-18 [52], and U–Pb ages, weighted means, and uncertainties were calculated and graphically presented using Isoplot/Ex [53]. All analytical data, containing mineral chemistry, zircon U–Pb age and peak metamorphic conditions, are listed in Tables S1–S3 of Supplementary Materials, respectively. Mineral abbreviations in the relevant figures and tables follow Whitney and Evans [54].

4. Estimates of Peak P–T Conditions for the Studied Samples

To better understand the grade and extent of regional metamorphism across the study area, 33 samples were selected to estimate the peak P–T conditions (Figure 1 and Table S1). These comprised 28 samples of garnet–mica schist and 2 samples of garnet–plagioclase amphibolite from the SSC, and 3 samples of felsic mylonite from the ZBLG. Considering the different mineral assemblages of these rocks (Figure 3a,b,e,h), the following thermometers and barometers were applied to evaluate the peak P–T conditions: (1) the garnet–biotite thermometer [55] (with an uncertainty of ±25 °C); (2) the garnet–biotite–plagioclase–quartz barometer [56] (with an uncertainty of 0.12 GPa); (3) the hornblende–plagioclase thermometer [57] (with an uncertainty of ±40 °C); (4) the garnet–hornblende–plagioclase–quartz barometer [58] (with an uncertainty of 0.11 GPa); and (5) the Ti-in-muscovite thermometer [59] (with an uncertainty of ±65 °C). To assure the reliability and validity of the P–T conditions estimated using these thermometers and barometers, 6 to 39 mineral pairs were selected for each sample to calculate P–T conditions. Uncertainties for P and T for each sample are presented as ±1 standard deviation of the mean. As this study focuses on the peak P–T conditions of the analysed rocks and peak equilibrium is assumed, prograde and retrograde metamorphic characteristics are not discussed.

4.1. Chemical Analysis of the Main Minerals

Establishing precise ‘peak’ compositions of minerals in P–T estimates is challenging due to the effects of decompression and mineral zoning [60]. For this reason, garnet, plagioclase, and biotite in a representative sample of garnet–mica schist (sample TS085) were examined in detail (Table S1 and Figure 4), with the results as follows.

(1) Garnet: Mg and Fe in garnet analysed using X-ray mapping exhibit slight zonal structure (Figure 4a,b). In the compositional profile (Figure 4c and Table S1), XFe and XMg gradually increase from 0.64–0.66 to 0.70–0.73 and from 0.04–0.05 to 0.07–0.09, respectively, from core to rim. XCa and XMn decrease from 0.23–0.25 to 0.20–0.17 and from 0.05–0.07 to 0.01–0.03, respectively. XMn displays a ‘bell-shaped’ pattern, corresponding to prograde zoning [60].

(2) Plagioclase: A backscattered electron image (BSE; Figure 4d) and compositional profile (Figure 4e) of plagioclase show a homogeneous pattern. In the core and rim (Table S1), XNa, XCa, and XK are ~0.84, ~0.16, and ~0.01, respectively.

(3) Biotite: A BSE image (Figure 4f) and compositional profile (Figure 4g) of biotite show a homogeneous pattern. In the core and rim, XMg, XFe, XAlVI, and XI are 0.45–0.47, 0.37–0.39, 0.12–0.14, and 0.03, respectively.

In accordance with Kohn [60], Wu [56], and Li and Wei [61], and on the basis of the mineral chemical analysis, garnet with the highest Mg/Fe²⁺ in its rim, biotite with the highest Fe/Mg, and plagioclase with the highest XCa can be considered to represent the compositions corresponding to peak metamorphism. Furthermore, the choice of the ‘peak’ compositions for amphibole and muscovite are according to the study from Shi [18,62].
Figure 4. X-ray mapping, backscatter electron (BSE) images and compositional profiles for garnet, plagioclase, and biotite from garnet–mica schist (sample TS085). (a,b) Mg and Fe X-ray mapping of garnet, respectively; (c) compositional profiles of garnet; (d,e) BSE image and compositional profile of plagioclase, respectively; (f,g) BSE image and compositional profile of biotite, respectively.
The compositions of the minerals used to calculate P–T values are presented in Figure 5 and Table S1. The $X_{\text{Ca}}$ and Mg/Fe$^{2+}$ values of garnet, the Ab, An, and Or contents of plagioclase, and the $X_{\text{Al}^{VI}}$ and Fe$^{2+}$/Mg values of biotite are $0.1$–$0.4$ and $0.05$–$0.23$, $73.40$%–$78.0$%, $15.50$%–$26.60$% and $0.50$%–$1.20$%, and $0.08$–$0.15$ and $0.64$–$1.27$, respectively (Figure 5a–c). The Mg/(Mg + Fe$^{2+}$) values of hornblende and Ti$^{4+}$ values of muscovite are $0.43$–$0.63$ and $0.1$, respectively (Figure 5e and Table S1). The compositions of all the minerals used to estimate P–T conditions are within the limits for minerals used in geothermobarometry (Figure 5) [56,57,59].

![Figure 5: Peak metamorphic compositional plots for the main minerals from the SSC samples.](image)

4.2. Peak P–T Conditions for the SSC

Peak metamorphic P–T conditions were estimated by using the thermometers and geobarometers given above. The peak P and T conditions estimated using methods ① and ② for 28 samples of garnet–mica schist and ③ and ④ for two samples of garnet–plagioclase amphibolite from the SSC are in the range of $P = 0.83$–$1.08$ GPa and $T = 476$–$620$ °C, with average $P$ and $T$ values of $0.98 \pm 0.07$ GPa and $531 \pm 35$ °C (Figure 6 and Table 1). In Figure 6, all samples plot in the field of epidote–amphibolite to amphibolite facies, corresponding to middle–lower crustal levels at $30$–$40$ km depth, defining an apparent geothermal gradient of $\sim 17$ °C/km. Estimates of the peak P conditions for the SSC calculated using ② and ③ are consistent with each other within the uncertainties associated with the two geobarometers (Figure 6) [56,58]. In contrast, the peak T conditions calculated using ① and ③ show an apparent discrepancy of up to $\sim 150$ °C (Figure 6 and Table S1). Two causes are suggested for the discrepancy in peak T estimation: (1) geological blocks or lenses with different metamorphic grades were tectonically juxtaposed during exhumation of the DOB; and (2) different geothermometers were used to estimate T for different types of rock. According to the present field survey and the results of Faure [2,3], Lin [63], and Ji [64], reason (1) can be disregarded on account of the lack of evidence for tectonic juxtaposition within the SSC.
Therefore, any possible peak $T$ discrepancy is ascribed to reason (2). By comparison, the peak $T$ values calculated by ① for 28 garnet-mica schists and ③ for two garnet-plagioclase amphibolites, respectively, are 476–576 °C and 612–620 °C (Figure 6 and Table S1), and it is obvious that the peak $T$ from ① is lower 40–150 °C than that of ③. However, it is noted that if the uncertainties of ±25 and ±40 °C for methods ① and ③, respectively, are taken into account, then the peak $T$ values obtained using methods ① and ③ give a more consistent temperature range of 500–580 °C, essentially eliminating the discrepancy. In other words, the peak $P$–$T$ values calculated using these ①–④ are the most reliable. After inspecting 30 samples from the SSC in detail, 23 samples fall into the epidote–amphibolite field, the exceptions being TS060, TS068, TS078, ZT005, ZT006, TS065-2, and TS074, which plot in the amphibolite field (Figure 6). These $P$–$T$ results imply that the SSC had mostly been metamorphosed under lower $T$ and relatively higher $P$ conditions. Meanwhile, an apparent geothermal gradient of ~17 °C/km suggest that the SSC belongs to the Barrovian-type metamorphism with medium-grade $P$ and $T$ (MPT) conditions.

4.3. Peak $P$–$T$ Conditions for the ZBLG

Peak $P$–$T$ conditions for the studied felsic mylonites (samples SS030, SS031, and SS035) from the ZBLG were also estimated. Only peak $T$ values were estimated because of the lack of sufficient mineral assemblages, using method ⑤ at a pressure of 0.5 GPa (following the estimation of $P$ by Shi [62]). Peak $T$ values of 392 ± 26, 350 ± 18, and 373 ± 33 °C were estimated, respectively, with an average of 372 ± 21 °C. The three samples plot in the greenschist-facies field (Figure 6 and Table S1). The $P$–$T$ values estimated for the SSC are clearly higher than those for the ZBLG (Figure 6), implying that the SSC and ZBLG were formed under different tectonic conditions.

![Figure 6. Estimated peak metamorphic $P$–$T$ conditions for the SSC and ZBLG. Red circles = garnet-mica schist; green circles = garnet-plagioclase amphibolite.](image-url)
Table 1. The peak metamorphic temperature and pressure for the SSC and the ZBLG.

| Sample  | T   | T_s | T_min | T_max | P   | P_s | P_min | P_max | Method | Mineral Pairs |
|---------|-----|-----|-------|-------|-----|-----|-------|-------|--------|--------------|
| TS028   | 478 | 8   | 466   | 487   | 0.94| 0.03| 0.88  | 0.98  | ① & ② | 10           |
| TS031   | 476 | 12  | 455   | 492   | 0.97| 0.04| 0.89  | 1.03  | ① & ② | 19           |
| TS032   | 521 | 14  | 503   | 546   | 1.02| 0.04| 0.94  | 1.09  | ① & ② | 21           |
| TS049   | 503 | 15  | 483   | 528   | 0.93| 0.03| 0.88  | 0.99  | ① & ② | 17           |
| TS051   | 525 | 13  | 509   | 550   | 0.84| 0.04| 0.77  | 0.90  | ① & ② | 13           |
| TS053   | 533 | 9   | 519   | 549   | 0.97| 0.06| 0.88  | 1.07  | ① & ② | 17           |
| TS056   | 547 | 8   | 528   | 558   | 1.08| 0.03| 1.02  | 1.13  | ① & ② | 14           |
| TS059   | 524 | 7   | 506   | 537   | 1.06| 0.03| 1.01  | 1.14  | ① & ② | 16           |
| TS060   | 558 | 7   | 548   | 577   | 0.92| 0.03| 0.90  | 0.98  | ① & ② | 14           |
| TS061   | 551 | 9   | 529   | 567   | 0.99| 0.03| 0.93  | 1.07  | ① & ② | 23           |
| TS065-3 | 525 | 11  | 509   | 550   | 1.06| 0.06| 0.96  | 1.19  | ① & ② | 23           |
| TS068   | 576 | 17  | 551   | 601   | 1.05| 0.03| 0.99  | 1.09  | ① & ② | 18           |
| TS077   | 540 | 12  | 523   | 561   | 1.05| 0.03| 1.00  | 1.11  | ① & ② | 17           |
| TS078   | 557 | 6   | 548   | 568   | 0.92| 0.02| 0.86  | 0.96  | ① & ② | 25           |
| TS082   | 498 | 9   | 475   | 511   | 1.01| 0.03| 0.97  | 1.07  | ① & ② | 13           |
| TS081   | 488 | 5   | 497   | 577   | 0.96| 0.02| 0.92  | 0.99  | ① & ② | 22           |
| TS080   | 528 | 6   | 518   | 540   | 0.86| 0.03| 0.81  | 0.90  | ① & ② | 11           |
| TS083   | 524 | 7   | 510   | 537   | 1.07| 0.02| 1.03  | 1.13  | ① & ② | 19           |
| TS084   | 493 | 13  | 471   | 512   | 0.91| 0.07| 0.83  | 1.04  | ① & ② | 21           |
| TS085   | 492 | 7   | 477   | 504   | 0.93| 0.03| 0.89  | 0.98  | ① & ② | 39           |
| ZT003   | 510 | 9   | 496   | 524   | 0.87| 0.03| 0.80  | 0.94  | ① & ② | 16           |
| ZT004   | 542 | 9   | 521   | 558   | 1.08| 0.03| 1.01  | 1.13  | ① & ② | 23           |
| ZT005   | 566 | 11  | 551   | 597   | 1.08| 0.05| 0.98  | 1.17  | ① & ② | 22           |
| ZT006   | 552 | 10  | 533   | 574   | 0.87| 0.04| 0.81  | 0.97  | ① & ② | 26           |
| ZT007   | 546 | 10  | 518   | 561   | 1.07| 0.05| 0.97  | 1.17  | ① & ② | 15           |
| TS079   | 534 | 17  | 510   | 569   | 1.03| 0.04| 0.95  | 1.11  | ① & ② | 25           |
| MQ033   | 522 | 14  | 487   | 552   | 1.00| 0.04| 0.93  | 1.05  | ① & ② | 28           |
| MQ034   | 499 | 27  | 458   | 555   | 0.94| 0.04| 0.87  | 1.05  | ① & ② | 20           |
| TS065-2 | 620 | 13  | 600   | 652   | 1.02| 0.05| 0.94  | 1.13  | ① & ② | 24           |
| TS074   | 612 | 17  | 572   | 636   | 0.91| 0.08| 0.64  | 1.01  | ① & ② | 20           |

The peak PT conditions for the SSC

\[ T = 531 \pm 35 ^{\circ}C \text{ and } P = 0.98 \pm 0.07 \text{ GPa} \]

The peak PT conditions for the ZBLG

\[ T = 372 \pm 21 ^{\circ}C \text{ and } P = 0.50 \text{ GPa} \]

5. Zircon U–Pb Dating for the SSC

5.1. Sample ZT003

Zircons from sample ZT003 have mostly oval, rounded, or prismatic morphology, lengths of 50–140 \( \mu \)m, and aspect ratios of 1:1 to 3:1. CL images show clear core–rim textures (Figure 7a). Thin rim domains without zoning indicate a metamorphic origin [65]. In contrast, core domains have faint oscillatory zoning, implying an igneous origin. A total of 104 analyses on 100 zircons yielded 71 ages ranging from 3065 ± 46 to 742 ± 15 Ma for core domains, with Th/U ratios of 0.14–2.0 (mostly > 0.4; Figure 7bc and Table S2). It is worth noting that 19 of their ages are discordant. The 71 ages can be divided into five age populations, defined as groups I, II, III, IV, and V, corresponding to ages of 3062–2684 Ma (n = 11), 2495–2393 Ma (n = 13), 2111–1827 Ma (n = 22), 1492–1231 Ma (n = 21), and 820–742 Ma (n = 4), respectively. Five peak mean ages of 2862, 2468, 2020, 1374, and 780 Ma, respectively, are shown in Figure 7d.
Figure 7. Cont.
6. Discussion

6.1. Spatial Pattern of Peak P–T Conditions

To establish the spatial variation in peak P–T values across the study area and understand the formation process of the DOB, the results of this study were combined with a compilation of previous results for peak P–T conditions and metamorphic ages from different units across the DOB (Figure 8 and Table S3). Using these results, profiles of geology and peak metamorphic P and T conditions were constructed across the southern margin of the DOB (Figure 9).

5.2. Sample ZT005

Sample ZT005 contains abundant oval, tapered, or elongated prismatic zircons that measure 60–160 µm in length and length-to-width ratios of 1:1 to 4:1. CL images reveal grey cores with sector or oscillatory zoning and brighter rims with faint oscillatory zoning, consistent with a magmatic origin (Figure 7c). A total of 112 analyses on 100 zircons yielded 91 ages ranging from 2971 ± 65 to 415 ± 12 Ma, with Th/U ratios of 0.10–1.58 (mostly > 0.4; Figure 7f,g and Table S2). Five analyses are discordant. The 91 zircon ages can be divided into six age populations, defined as groups I, II, III, V, IV and VI, corresponding to ages of 2971–2933 Ma (n = 2), 2703–2341 Ma (n = 19), 2122–1956 Ma (n = 27), 1424–1291 Ma (n = 37), 915–810 Ma (n = 4), and 427–415 Ma (n = 2), respectively (Figure 7f). Six peak mean ages of 2963, 2475, 2019, 1356, 899, and 425 Ma, respectively, are presented in Figure 7g.

5.3. Sample ZT006

Zircons from sample ZT006 have prismatic or euhedral morphology, lengths of 20–110 µm, and aspect ratios of 3:1–4:1. A complex core–rim texture is revealed by CL images (Figure 7i). Core domains with oscillatory or planar zoning are characterised by a grey or dark colour, implying a magmatic origin. Rim domains with blurred spongy and flow zoning may be of metamorphic origin [66–72]. A total of 55 ages ranging from 2072 ± 35 to 190 ± 5 Ma were obtained from 86 analytical spots on 100 zircons (Figure 7j and Table S2). A total of 22 age determinations on cores yielded ages of 2072 ± 35 to 418 ± 10 Ma, and 23 determinations on rims yielded ages of 259 ± 6 to 190 ± 5 Ma, with Th/U ratios of 0.20–1.70 and 0.003–0.08, respectively (Figure 7k). Five age populations can be identified, defined as groups I, II, III, IV, and V, corresponding to 2072–1902 Ma (n = 3), 1315–1238 Ma (n = 2), 850–690 Ma (n = 10), 475–418 Ma (n = 7), and 259–190 Ma (n = 23), respectively (Figure 7j). Five peak mean ages of 1991, 1285, 751, 441, and 211 Ma, respectively, are presented in Figure 7g.
tively, are presented in Figure 7k. On the basis of CL images and Th/U ratios (all < 0.1) of zircons in Group V, the ages of 259–190 Ma (Group V) are interpreted to reflect the timing of metamorphism in the SSC.

6. Discussion
6.1. Spatial Pattern of Peak P–T Conditions

To establish the spatial variation in peak P–T values across the study area and understand the formation process of the DOB, the results of this study were combined with a compilation of previous results for peak P–T conditions and metamorphic ages from different units across the DOB (Figure 8 and Table S3). Using these results, profiles of geology and peak metamorphic P and T conditions were constructed across the southern margin of the DOB (Figure 9).

Figure 8. Zircon U–Pb ages for metamorphic rocks in the Dabie orogenic belt. Refs. [73–78] for eclogite ages.

The spatial distribution of peak P–T conditions across the study area (Figure 9 and Table S3) reveals three distinct P–T regions: 0.50 GPa and 372 ± 21 °C for the ZBLG, 0.98 ± 0.07 GPa and 531 ± 35 °C for the SSC, and 2.40 ± 0.24 GPa and 521 ± 50 °C for the SDMB [45]. Taking into account the uncertainties associated with estimating P–T conditions, the estimates for the ZBLG and SSC differ by ~0.4 GPa and ~100 °C, implying that these units formed in different tectonic environments (Figure 9b,c). Shi [62] suggested that the ZBLG could have been formed by dynamic metamorphism resulting from movement on the TanLu fault during the Late Jurassic and should, therefore, not be attributed to the DOB. In contrast, there is a difference in P of 1.11 GPa between the SDMB and SSC, which is equivalent to a ~35 km thickness loss (Figure 9b,c), but not in T. One possible reason is from their different subducted depth and environments.
Figure 9. Profiles of geology (a), peak metamorphic $T$ (b), and peak metamorphic $P$ (c) across the southern margin of the Dabie orogenic belt.
From south to north across the SSC, peak $P$–$T$ values show a smooth trend without substantial spatial variation, and focus on the range of ~0.9–1.10 GPa and ~500–570 °C defined by average $PT$ conditions and errors for the SSC (Table 1 and Figure 9b,c). This result indicates that the SSC as a whole was subducted to middle–lower crustal levels of 30–40 km depth (Figure 9c). If taking into account an apparent geothermal gradient of ~17 °C/km, the SSC should be formed by ‘warm’ subduction at a shallow level (Figure 6).

In contrast, the SDMB was subducted into the overlying subcontinental lithospheric mantle (SCLM) at depths of ~70–90 km, and located in the ‘cold’ subduction defined by an apparent geothermal gradient of <10 °C/km (Figure 9 and Figure 11a,b) [45]. Hence, these differences lead to a larger $P$ gap and similar $T$ among the SDMB and the SSC. This result implies that the transitional subduction from shallow to deep subduction occurred at the Moho level (Figure 11a,b).

6.2. Formation Age and Genesis of the SSC

The SSC has been regarded as late Palaeoproterozoic according to contact relationships between stratigraphic units [8]. However, the identification of Neoproterozoic granitic gneisses [49] and Mesoproterozoic plagioclase amphibolites [50] has suggested that the SSC may have formed during or after the Neoproterozoic. In this study, zircon U–Pb dating of three garnet–mica schist samples ZT003, ZT005 and ZT006 from the SSC yield five, six and five age groups, respectively, which mostly concentrate on the Meso-Neoarchean, early-middle Paleoproterozoic, middle Mesoproterozoic, Neoproterozoic, Palaeozoic and Triassic and indicate a complex age provenance (Figure 7 and Table S2). Combining with the analyses of CL images and Th/U ratios for zircons from these schists, except for Group V zircons with the metamorphic origin (Th/U ratios of <0.1) of the ZT006, all the others are detrital zircons with magmatic origin (Figure 7a,c,e,g,i,k and Table S2). Hence, as mentioned above, an age population of 259–190 Ma (Group V) from sample ZT006 represents a metamorphic age for the SSC. However, given 240–200 Ma [4] for the DOB formation time limit and 251–228 Ma for the peak metamorphic age of the SSC [19,79], the 259–190 Ma age population is inferred to include the timings of both peak and retrograde metamorphism for the SSC. Furthermore, the two youngest age populations of 427–415 Ma (Group VI) and 475–418 Ma (Group V) from samples ZT005 and ZT006, respectively, suggest that the formation age of the SSC could be Middle Devonian, equivalent to that of the Foziling Group [22,24,32].

For convenience, the zircon data from the three analysed samples were pooled for statistical analysis and comparison (Figure 10a). In addition, the formation ages of various orthogneisses and meta-basic and pelitic rocks exposed across the DOB were compiled from previous studies to investigate possible provenance regions for the SSC (Figure 8). Rocks ranging in age from Neoarchean to Palaeozoic are exposed in the DOB. Figure 8 shows that 0.9–0.7 Ga granitic gneisses are widely distributed across the various geological units of the DOB [21,22,32,36–39,49,80–85]. In addition, some 2.0 Ga granitic gneisses, as well as 1.84 and 1.38 Ga meta-basic rocks, occur in the SSC [20,50], and minor 2.0 Ga granulite and 1.98 Ga gneisses occur in the NDMB [86]. Sporadic Palaeozoic granites (457 ± 2 Ma) and 2.5 Ga granitic gneisses crop out in the Jinzhai area of the BHYMB and the Xishui area of the DBC [48,87], respectively (Figure 8).
Figure 10. Diagrams showing zircon ages for the SSC and Foziling Group. (a) Zircon age histogram for the three samples of garnet–mica schist (samples ZT003, ZT005, and ZT008) analysed in this study; (b) comparative plot of zircon ages for the SSC and Foziling Group; (c) schematic diagram illustrating the provenance of zircons and inferred genesis of the SSC and Foziling Group.
Seven peak mean ages of 2867, 2475, 2011, 1368, 744, 441, and 211 Ma are defined by 207 zircons from the three analysed samples (Figure 10a). Except for the 211 Ma, all the others correspond to those of possible age provenance regions across the DOB (Figure 8). In particular, the 744 Ma falls within the range of 0.9–0.7 Ga, implying an affinity with the YZB [4,88–90]. This correspondence suggests that, possibly, multiple provenance areas of the SSC were in the DOB or YZB (Figure 10c). Therefore, combining with the previous structural analyses [3,24,63,64], it is suggested that the SSC initially exists as a sedimentary cover on the passive continental margin in the northern YZB during the late Palaeozoic. Comparing the SSC with the late Palaeozoic Foziling Group in the northernmost DOB [22,24,31,32,91], zircon ages from these two units both contain age populations of 2.6–2.4, 2.1–1.8, 1.4–1.2, 0.9–0.7, and 0.5–0.4 Ga (Figure 10b), suggesting that the SSC and Foziling Group were formed in similar tectonic environments. Therefore, a simplified scenario is suggested for the formation of the SSC and Foziling Group (Figure 10c). Both units were initially deposited as sedimentary rocks on the passive margin of the YZB during the late Palaeozoic, and their provenance was the YZB basement, which is composed mainly of Neoproterozoic granitic gneiss with minor Palaeo–Mesoproterozoic rocks and Palaeozoic intrusions (Figure 10c). However, this interpretation is inconsistent with the ‘independent micro-continent’ model for the formation of the Foziling Group [22,24]. This model defines the Foziling Group as an independent terrane located between the YZB and the North China block (NCB), mainly on the basis of 0.50–0.40 and 2.6–2.4 Ga zircon ages [92–95] originating from an independent island arc [22] and the NCB, respectively. However, the existence of 457 ± 2 Ma [87] and 2.5 Ga [48] rocks in the DOB indicates that these zircons all have a YZB provenance, and rejects the model (Figure 8).

6.3. The Transitional Subduction from the Shallow to the Deep Levels for the DOB

The DOB was formed by the subduction and exhumation of multi-slices with different peak metamorphic grades and ages along a subduction channel [28,96,97], and has been considered as a typical collisional orogen resulting from deep continental subduction (Figure 11a) [4,5]. However, in view of the peak P–T conditions (Figure 8 and Table S3), these slices can be divided into two parts: the HP-UHP and the MPT units. The former contains the SDMB, CDMB-I, CDMB-II and NDMB, corresponding to peak P–T values of 2.40 GPa/521 °C, 3.09 GPa/613 °C, 3.87 GPa/728 °C, and 4.50 GPa/857 °C [32,45,73,74], respectively (Figure 11a,b and Table S3). At the same time, an apparent geothermal gradient of ~7 °C/km defined by these units was gained. This result indicates that the HP-UHP units underwent Alpine-type metamorphism under ‘cold’ subduction environments [98–100] and had subducted into the SCLM and asthenosphere levels, representing deep continental subduction (Figure 11a,b and Table S3). The MPT units, on the other hand, are composed of the SSC and Foziling Group, with peak P–T values of 0.98 GPa/531 °C and 0.71 GPa/570 °C, respectively (Figure 11a,b and Table S3). Considering two apparent geothermal gradients of 22 and 17 °C/km for the SSC and Foziling Group, respectively, the MPT units had only subducted into the middle-lower crust depths of 20–40 km, and experienced Barrovian-type metamorphism under ‘warm’ subduction environments, thus representing shallow subduction (Figure 11a,b). Obviously, the subduction of the DOB comprises the shallow and deep subductions.

The peak metamorphic ages of the Foziling Group and SSC are 270–260 Ma [3,23,75] and 251 Ma [19], respectively (Figure 8). The age from the Foziling Group may represent the timing of the initiation of the subduction of the YZB beneath the NCB, whereas the age for the SSC may represent the cessation of subduction at crustal levels (Figure 11b). The difference in the peak metamorphic ages between the Foziling Group and the SSC (Figure 11b) suggest that shallow subduction might have been sustained for up to ~19 Myr. If a burial depth of ~35 km is assumed from the average peak P value for the SSC (Table S1 and Figure 11a,b), a burial rate of ~1.8 mm/yr is obtained. In comparison, the ages of peak metamorphism of the SDMB, CDMB-I and -II, and NDMB are 242–236 Ma [46,78],
238–226 Ma [76,77], and 226–218 Ma [28,73], respectively, all of which are younger than those of the Foziling Group and SSC (Figures 8 and 11b). A ~24 Myr duration of deep subduction can be defined on the basis of the maximum difference in these ages (Figure 11b). A burial rate of ~6.3 mm/yr can be calculated using an assumed subduction depth of ~150 km, based on the average peak $P$ value for the NDMB (Figure 11b).

Figure 11. Schematic diagrams illustrating the mechanism for the distribution of peak $P$–$T$ conditions. (a) Peak $P$–$T$ conditions for the units of the DOB; (b) sketch map showing subduction and exhumation of the units; (c) present configuration of the tectonic units, modified after Faure [3]. The black line with an arrow in (a) represents the transition from shallow to deep subduction at the Moho level.

Differences of at least ~1.1 GPa (Figure 9c), 10 °C/km (Figure 11a), and ~4.5 mm/yr for the peak $P$ value, geothermal gradient, and burial rate, respectively, exist between the MPT and HP–UHP units. These values imply that there was a sharp change in conditions associated with the transitional subduction from shallow to deep levels. In the present case, several possible mechanisms could have been involved in the transition: (1) breakoff between continental and oceanic slabs [101]; (2) tectonic transition from continental subduction to continental collision [102]; and (3) a change in subduction dip angle [103]. Mechanisms (1) and (2) define the transition from oceanic or continental subduction to collision [101,102]. However, the ages of the peak metamorphism of the MPT and HP–UHP rocks within the DOB show that these units were in a successive or continuous subduction environment without a change in tectonic setting (Figure 11b) [2,3], contrary to the prediction of mechanisms (1) and (2). In comparison, mechanism (3) is better able to explain the transitional subduction. Chen [103] considered that a change in subduction dip angle, as defined by a varying geothermal gradient over time, generated the differences in metamorphic grade and age. For example, in the western Himalaya, older UHP and younger HP rocks resulted from a coherent change in subduction dip angle from steep to gentle for the India plate. With respect to the geochemical gradients estimated in this study, the geothermal gradients of 17–22 °C/km and 7 °C/km from the MPT and HP-UHP units, respectively, may correspond to low-angle and steep subductions (Figure 11a,b). Hence, the transitional subduction from the shallow to deep levels is due to a change in subduction dip angle, and result in older MPT and younger HP-UHP units.
A subduction process with non-uniform velocity for the DOB is suggested from 1.8 mm/yr and 6.3 mm/yr burial rates for the shallow and deep subductions, respectively. It is speculated that this process was associated with a changing dip angle of subduction and differing resistance to subduction, by comparison with studies of the Himalayan orogenic belt [104,105]. During shallow subduction, the MPT units were subducted at a low angle to shallow crustal levels and collided with the rigid crust of the NCB (Figure 11b), which resisted the subduction, leading to a marked decrease in burial rate and the termination of subduction. In contrast to the shallow subduction, the HP–UHP units were rapidly subducted at a steep angle into the plastic SCLM–asthenosphere pulled down by the Palaeotethys oceanic plate [24], which offered limited resistance to subduction, allowing deep subduction and leading to a more rapid rate of burial. According to the peak P–T conditions and ages of peak metamorphism (Figure 8; Figure 11a,b), the transitional subduction from shallow to deep levels is interpreted to have occurred at the Moho level during the Early Triassic (Figure 11b). The present-day distribution of these MPT and HP–UHP units across the DOB reflects the status of exhumation subsequent to subductions (Figure 11c), and the integrity of these units has also been affected by sinistral shearing along the Xiaotian–Mozitan fault, and partial melting of the NDMB [7,29,43,91].

7. Conclusions

The SSC, composed of schists, granitic gneisses, marbles, and minor meta-basic rocks, underwent epidote–amphibolite- to amphibolite-facies metamorphism with average peak P–T conditions of 0.98 ± 0.07 GPa and 531 ± 35 °C. The smooth spatial pattern of the peak P–T conditions and an apparent geothermal gradient of ~17 °C/km suggest that the SSC belongs to the Barrovian-type metamorphism.

Zircon U–Pb dating for three garnet–mica schist (sample ZT003, ZT005 and ZT006) from the SSC yield a lot of age groups, indicating complex age provenances. Zircons with Th/U ratios of <0.1 from sample ZT006 give an age population of 259–190 Ma (Group V), recording the timings of both peak and retrograde metamorphism for the SSC. Except for the above, all the others are detrital zircons with magmatic origin, the ages of which are all from age provenances within the DOB or YZB. Moreover, the two youngest age populations of 427–415 Ma (Group VI) and 475–418 Ma (Group V) from samples ZT005 and ZT006, respectively, define the formation age of the SSC at Middle Devonian. The similarity of the formation age of the SSC to that of the Foziling Group, located in the north margin of the DOB, confirms that both were initially deposited as sedimentary cover on the passive continental margin in the northern YZB during the late Palaeozoic.

On the basis of the peak metamorphic P–T conditions and ages for different units, the DOB consists of HP-UHP and MPT (i.e., the SSC, Foziling Group) units, representing shallow and deep subductions, respectively. Meanwhile, variation in apparent geothermal gradients and burial rates from 17–22 °C/km and ~1.8 mm/yr to 7 °C/km and ~6.3 mm/yr for the MPT and HP-UHP units were obtained, respectively. These results reveal a transitional subduction from the shallow to deep levels during the formation of the DOB. Furthermore, it is inferred that the transitional subduction occurs at Moho depths during the Early Triassic, and result from a change in subduction dip angle.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min12101201/s1. Table S1: The representative electron-microprobe analyses for main minerals of samples across Susong Complex rocks and Zhangbaling Group; Table S2: The detrital zircon U–Pb ages for three garnet mica schists from the SSCR; Table S3: The peak metamorphic PT-conditions for the various units across the Dabie orogeny.

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