

# Mechanisms for the Formation of Metamorphic Temperature and Pressure Gradients in Orogenic Belts

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## Abstract

P-T trajectories based on depth-controlled metamorphism have been questioned by some scholars, as they only consider static rock pressure and ignore fluid pressure, tectonic stress, and thermal pressure. In this paper, based on the arch tectonic dynamics model of Basin Mountain evolution and the theory of neutrino oscillation-induced radioactive decay and magma formation, we propose the temperature and pressure gradient formation mechanisms of metamorphism in orogenic belts and provide a new explanation for the formation of paired metamorphic belts. This mechanism shows that, due to the arch tectonic effect, a high-pressure or even ultra-high-pressure environment is formed at the edge of the mountain range, while a low-pressure environment is formed in the belly of the mountain range. At the same time, due to the stress difference between the edge and the belly of the mountain range, magma (heat) from the deep mantle and the asthenosphere will migrate and converge from the high-pressure area below the edge of the mountain range to the low-pressure area in the belly of the mountain range, thus forming the high-pressure, low-temperature zones where magma is lacking, and low-pressure, high-temperature zones where magma converges, respectively, and giving rise to corresponding metamorphic effects.

## Keywords

Orogenic Belts, Arch-Tectonic Effects, Metamorphism, Ultra-High-Pressure and High-Temperature Formation Mechanisms, Paired Metamorphic Belts

## 1. Introduction

Since Miyashiro (1961, 1972) correlated the P-T conditions of metamorphic rock

formation with the tectonic setting in which it occurred and introduced the concept of metamorphic facies series, it has been widely recognized that metamorphism is controlled by depth (or geothermal gradient) (England & Thompson, 1984). Based on this understanding, it is possible to estimate the P-T conditions at the time of metamorphism from the metamorphic rocks and thus determine the depth of metamorphic formation. For example, coesite is found in the glaucophane schist of the Dora Maira Massif in the Western Alps orogenic belt, which can be inversely inferred to have formed at a depth of about 80 km based on the static pressure gradient (Chopin, 1984). To reach this depth, it is usually assumed that the only way is to rely on plate subduction. Therefore, paired metamorphic belts and high-pressure-ultra-high-pressure metamorphic belts have been generally recognized as the main signatures of plate subduction zones and one of the important bases of plate tectonic theory (Cawood, 2020; Zhang et al., 2021b; Zheng et al., 2022).

Both the use of subduction to explain the formation of paired metamorphic belts and high-pressure-ultra-high-pressure metamorphic belts and the use of paired metamorphic belts and ultra-high-pressure metamorphic belts as evidence for subduction are premised on the assumption that depth is the only controlling factor for metamorphism. However, the idea that depth controls metamorphism has been questioned (Wang, 1996; Wu & Chi, 2003; Moulas et al., 2014, 2022; Chu et al., 2017; Putnis et al., 2021; Lü et al., 2017, 2024; Zou et al., 2025). These queries focus on three main areas:

i) pressure is not only a function of depth but is also related to factors such as fluid pressure, tectonic and thermal stresses (Zhuang, 1994; Luisier et al., 2019; Lü et al., 2024). Zou et al. (2025) showed that the rapid dewatering response of minerals may lead to localized fluid pressures exceeding static rock pressures. Numerical simulations show that when low-permeability metamorphic rocks are rapidly heated, fluids released by dehydration accumulate in confined spaces and can create localized overpressures higher than 0.45 GPa over hundreds of years. This overpressure is equivalent to adding an extra dozen kilometers of rock to the crust. Zhuang (1994), researching the Qilian mountain belt Gaolan Group and Altai Orogenic Belt, shows that the formation of incremental metamorphic zones has nothing to do with depth but is related to the rise of regional thermodynamic anomalies in the orogenic belt, and that the intensity of metamorphism is related to the spatial distance between the centers of regional thermodynamic anomalies. The petrological model of the continental lithosphere of the Qinling Luoyang-Yichuan-Shiyan-Zigui geologic section established by Wang et al. (1995) shows that geothermal temperatures (or geothermal temperature gradients) are not the same at the same depths; for example, at a depth of 30 km, the geothermal temperature of the North China Craton is 300°C, whereas those of the North Qinling Orogenic Belt and the Yangzi Craton are 450°C and 400°C, respectively. Obviously, thermal stresses vary with temperature.

ii) The lithostatic pressure gradient calculates that eclogite formed at a depth of

at least 70 km, eclogite containing coesite at a depth of at least 120 km, and eclogite containing both coesite and diamond at a depth of at least 145 km. The plate subducted to these depths and returned to the surface, lacking a dynamical mechanism (Malusà et al., 2015; Tang & Hou, 2016; Zhou et al., 2020). Taking a step back, even if subduction into the deep mantle generates a mineral like coesite, a rapid return to the surface is necessary to ensure that it does not degenerate into quartz. However, subduction-return takes at least a million years, and as the pressure in the return decreases, coesite will inevitably regress to quartz (Wu & Chi, 2003; Su, 2011; Yang, 2015). Therefore, some scholars have argued that the relationship between pressure and depth of the crust cannot be determined simply from thermodynamic modeling of mineral assemblages. Tectonic additional stresses in the crust (Tang & Hou, 2016; Lü et al., 2017), microstructural overpressure (Wu & Chi, 2003; Moulas et al., 2014), extraordinary pressures in confined spaces (Su, 2011; Zou et al., 2025), and earthquake-induced overpressure (Yang et al., 2014; Yang, 2015), all are able to cause the pressure in the crust to deviate from the static rock pressure.

iii) Some scholars have also proved experimentally that ultrahigh-pressure minerals can be formed in the shallow layer of the Earth's surface without subduction into the deep mantle. The experimental results of Zhou et al. (2005) show that, under an experimental confining pressure of 1.3 GPa, a temperature of 950°C - 1000°C, a differential stress of 1.5 - 1.67 GPa, and a strain of 75% - 81%, fine-grained coesite appeared in the plastically deformed experimental samples of quartzite; therefore, the pressure at which coesite appeared under differential stress was much smaller than that at which coesite stabilized under hydrostatic pressure. Su et al. (2006) used a combination of high-energy mechanical ball milling and static high pressure to simulate surface coesite synthesis experiments, and found that there is a mechanical ball milling time threshold and an intermediate sub-stable phase of  $\alpha$ -quartz induced by mechanical collision, whose static high-pressure crystallization into coesite occurs at 3.0 GPa, 923 K, and less than 1.0 min; meanwhile, they found a 10 s magnitude short-time rapid synthesis phenomenon of coesite. Such overpressure and temperature conditions can be achieved in meteorite impacts, earthquakes, and volcanoes.

In addition, field geological observations, tectonic geology, metamorphic petrology, isotope geology, geochemistry, geophysics, and physical experiments have shown (Zhang, 2021) that ultrahigh-pressure metamorphism usually occurs within the Earth's crust rather than in the upper mantle, and that ultrahigh-pressure metamorphic rocks containing coesite are located only in tectonic slices about 10 - 12 km below the upper crust, and that they are either related to multi-level shearing or caused by intense shearing. It can be seen that subduction is not the only condition or mechanism for the formation of coesite.

In response to the above problems, in this work, we analyze the force actions and magmatic activity of rocks in the orogenic belt using mechanical models, discuss the distribution of non-depth-controlled temperature-pressure gradients

within the crust, and propose a mechanism for the formation of ultrahigh-pressure and ultrahigh-temperature environments within the crust.

## 2. Method

Based on the arch-shaped structural-dynamic model of basin-mountain evolution (Zhang & Zhang, 2024a, 2025) and the new theory of magma formation (Zhang & Zhang, 2024b), the stress situation of crustal rocks in orogenic belts, the direction of magma migration and convergence, as well as the distribution of temperature and pressure, were analyzed, and the formation mechanism of orogenic belt metamorphism was proposed.

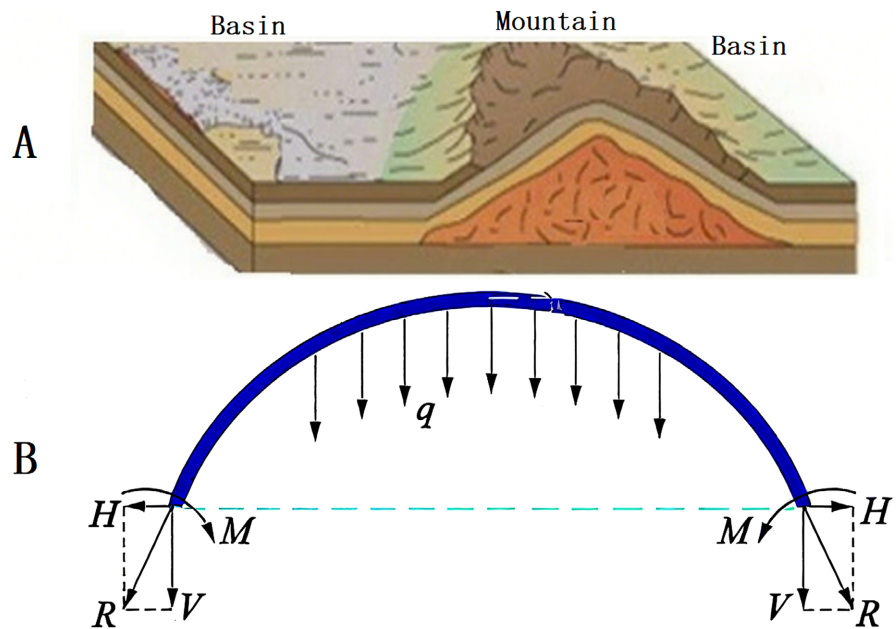
### 2.1. Arch-Tectonic Modeling and Force Analysis in Orogenic Belts

Zhang and Zhang (2024a, 2025) established an arch tectonic dynamics model for basin-mountain coupling in their study of basin-mountain coupling evolution. They argued that the basin-mountain-basin (e.g., Tarim-Tianshan-Junggar) composed of the basin-mountain system constitutes an arch, which creates differences in the stress distribution of the basin-mountain system. The mountain range is the arch, and the basins (or flatlands) on both sides of the mountain range are the foot of the arch (Figure 1(A)). The arch (mountain range) is able to convert its huge gravity into lateral compression force (i.e., circumferential stress) to be transmitted to the basins on both sides, so that the edge of the mountain range and the basins are subjected to much greater pressure than the hinterland of the mountain range. The stress difference generated by this arch tectonic effect provides a power mechanism for basin subsidence and mountain range uplift. The usual force characteristics of arch tectonics are: under the vertical load  $q$  of the arch tectonics, the bearing point produces not only the vertical reaction force  $V$ , but also the horizontal thrust force  $H$  (Figure 1(B)). As a result of this horizontal thrust, the bending moment of the arch is much smaller than that of a horizontal beam of the same span, so that the whole arch construction is mainly under compressive stress. If the arch construction material is hard enough, the full weight of the arch can be transferred to the foot of the arch on both sides through circumferential stresses, so that the pressure carried by the foot of the arch increases significantly, while the stress under the arch construction is greatly reduced, and can even be zero (Mao et al., 2020).

In the basin-mountain-basin arch tectonic system, the vertical height of the arch is usually much smaller than the lateral span of the arch, and such a low curvature will weaken the effect of the arch tectonics; however, because the Earth itself is nearly spherical and has a certain curvature that amplifies the arch tectonics of the basin-mountain system, the effects of the stress transformations will be significant even if the curvature of the basin-mountain-basin arch tectonics is small (Mao et al., 2020).

Arch structure is mainly composed of rocks with a certain degree of rigidity. The upper crust is the main body of the arch structure; the middle and lower

crust and lithospheric mantle have a certain contribution to the arch structure. The asthenosphere beneath the lithosphere is easy to flow or creep and is difficult to resist the shear effect, so the thickness of the arch structure is basically generally not greater than the thickness of the lithosphere. The thickness of the Earth's lithosphere is 0 - 80 km (local variations of 5 - 200 km), and the lithosphere's own gravity-induced stress distribution is about 3 GPa on average. According to the elastic buckling load formula, the maximum critical elastic buckling load that the lithosphere of different compositions can withstand does not exceed 30 MPa.



**Figure 1.** Stresses on arch constructions. Image cited in Zhang and Zhang (2024a).

(Li & He, 2022). Therefore, the lithosphere cannot withstand its own gravity. Fortunately, it is supported by the underlying mantle and the asthenosphere, so that the lithosphere is usually in a state of mechanical equilibrium. In regions with arch structures (e.g., basin-ranges-basin systems), the gravity of the lithosphere is partially shifted from directly below the arch structures to the sides, which causes the mantle and the asthenosphere below the basins to be subjected to higher stresses than those below the ranges, which results in the plastic mantle and the asthenosphere melts being extruded and flowing slowly from the basins on both sides to the bottom of the mountain ranges (Zhang & Zhang, 2025).

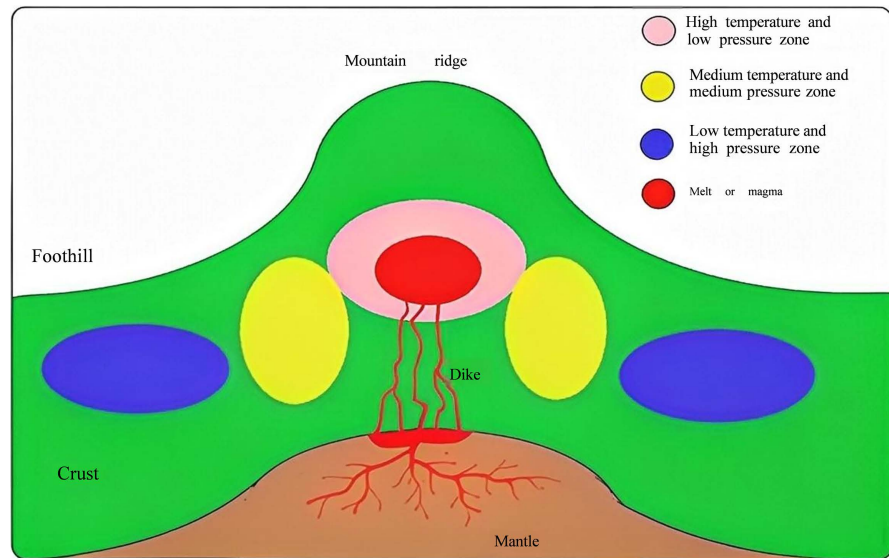
## 2.2. Mechanisms of Magma Migration, Convergence and Formation of Temperature-Pressure Gradients in Orogenic Belts

Wolfenstein (1978), Mikheyev and Smirnov (1989) showed that when neutrinos propagate in matter, when the energy of the neutrinos matches the density of the matter, the neutrinos can form an MSW (Mikheyev-Smirnov-Wolfenstein) resonance with the matter atoms, thus increasing the neutrino flavor transition

probability. Zhang and Zhang (2024b; 2024c; 2025) further investigated that the MSW resonance is actually a typical physical resonance with energy excitation. While increasing the probability of neutrino flavor conversion, this resonance also has an effect on the propagation medium, exciting unstable radioactive nuclei in it and increasing the probability of their decay, thus releasing more heat and causing some of the material to melt (forming magma). Calculations based on MSW resonance conditions and the content of radioactive materials in various layers of the Earth show that magma can be formed only when atmospheric neutrinos resonate with upper mantle materials in MSW, and therefore magma generally originates in the upper mantle (including the asthenosphere). Once formed, the magma migrated upward under buoyancy. Initially, the magma produced is sporadic and dispersed, and as more molten material is produced, some of the magma converges with each other. In the plastic mantle, magma usually migrates by infiltration; after arriving at the rigid lithosphere, the permeability barrier at the lithospheric boundary blocks its ascent, so magma can hardly rise by infiltration and can only move upward along fissures or fractures, invade the crust and solidify to form plutonite, interact with sedimentary layers to form metamorphic rocks, or move along fissures directly to the surface to form volcanic eruptions. Using this theory of magma formation, Zhang and Zhang (2024b; 2025) better explained the formation of inner and outer Earth tectonics such as the asthenosphere, the Lithosphere-Asthenosphere Boundary (LAB), the new oceanic crust of mid-oceanic ridges, and the striped magnetic anomalies and Oceanic Core Complexes (OCC).

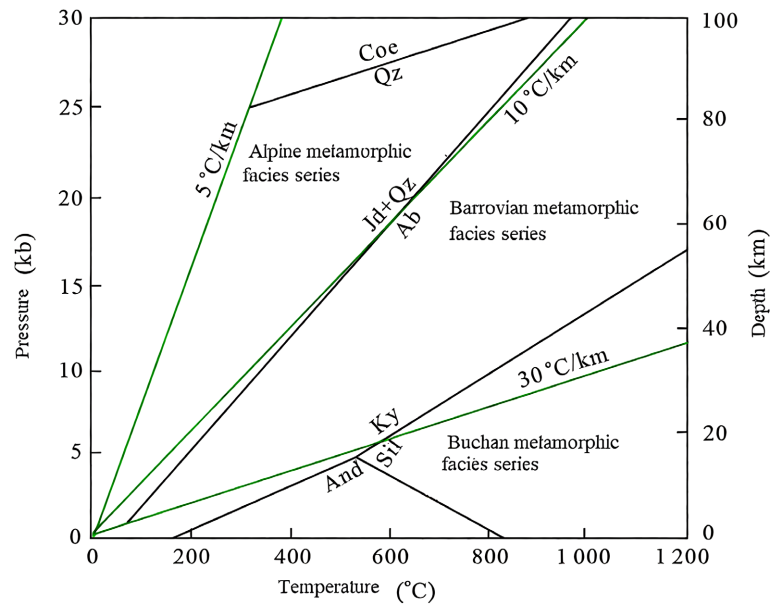
In the orogenic belt, due to the arch tectonic effect, the rock layers at the edge of the mountain range and below the basins on both sides are subjected to higher stresses than those below the mountain range's hinterland (Zhang & Zhang, 2024a, 2025). Under the effect of this difference in stresses, magma migrates from the basins on both sides and the edge of the mountain range to the mountain range's hinterland, and converges below the mountain range's lithosphere. With the increase of magma convergence, there are two main effects: first, the magma heats and softens the overlying rocks, which increases their plasticity; second, the thermal pressure increases, which squeezes the overlying rocks, leading to uplift of the overlying rock layers and pushing the mountain range to grow taller. The uplift of the overlying rocks makes room for the magma that rises later. Thus, below the belly of the mountain range, more and more magma collects. Of course, the magma in the uppermost layers also solidifies as it dissipates heat, forming new plutonic rocks and undercutting the overlying rock layers, causing them to rise or fracture. In this way, the magma will rise along the cracks and squeeze the rock cracks, resulting in further enlargement of the cracks and opening up new space for the magma to rise. In short, the arching tectonic effect of the orogenic belt causes magma from the mantle and the asthenosphere to flow continuously into the belly of the mountain range, and to gradually encroach on the upper part of the belly. As a result, three distinct regions of temperature and pressure gradients are cre-

ated in the orogenic belt. Below the belly of the mountain range, due to the convergence of magma, (red circled area in **Figure 2**).



**Figure 2.** Map of the distribution of different temperature and pressure regions in the crust beneath the mountains (the ellipses in different colors are shown only for ease of discussion and illustration; the actual distribution of metamorphic zones is not elliptical but rather irregular).

Temperatures are higher, but, being directly below the arch tectonics of the mountain range, stresses are minimized, so a high-temperature, low-pressure environment results (**Figure 2** Pink portion of the magma perimeter). At the edge of the mountain range (blue ellipse in **Figure 2**), a high-pressure, low-temperature environment is created because it is far away from the magma area and is at the foot of the mountain range, where lateral stresses are the highest. The zone between the edge of the mountain range and the belly of the mountain range (yellow ellipse in **Figure 2**) is closer to the magma convergence area and is subject to lower lateral stresses than the foothills and higher lateral stresses than the belly of the mountain range, resulting in a medium-temperature, medium-pressure zone. For example, in the paired metamorphic belts exposed in the eastern section of the Dabie Mountains in China, high-pressure, low-temperature metamorphic rocks are mostly located at the margins of the mountain ranges, while low-pressure, high-temperature hornblende-phase rocks are mostly located in the central part of the mountain ranges and are associated with granites (Ma & Zhang, 1988). Currently, metamorphism is categorized into three series based on P-T trajectories, i.e., the Alpine metamorphic series with a low thermal gradient (low T/P value), the Barrovian metamorphic series with a medium thermal gradient (medium T/P value), and the Buchan metamorphic series with a high thermal gradient (high T/P value) (**Figure 3**) (Zheng & Chen, 2017; He & Zheng, 2019). These three series correspond to the blue, yellow, and pink areas in **Figure 2**, respectively.



**Figure 3.** Phase diagram for regional metamorphic rocks in three facies series at different thermal gradients. Image cited in [Zheng and Chen \(2017\)](#) and [He and Zheng \(2019\)](#).

### 3. Results and Discussion

From the previous discussion, it can be seen that the heat of metamorphism mainly comes from magma. The formation of UHP is closely related to both the stress formed by arch tectonics and the thermal and fluid pressures generated by magma.

#### 3.1. Heat Source

A heat source is one of the most important conditions for metamorphism, especially for high-temperature and low-pressure metamorphic conditions, which require an additional heat source. Regarding the heat supply mechanism of metamorphism, it is usually believed by previous authors ([Dewey & Bird, 1970](#); [England & Thompson, 1984](#); [Wen et al., 2020](#)) that the heat originates from the heat conduction of crustal thickening, including internal radiative heat as well as conductive heat from the bottom of the crust ([England & Thompson, 1984](#)) or localized radiative anomalous heat gain ([Engi et al., 2001](#)). Such heat supply is a gradual and cumulative process, so the metamorphic time of metamorphism is generally around 50 Ma or longer ([England & Thompson, 1984](#); [Wen et al., 2020](#)). However, short-term, multi-acting thermal events in the Grampian orogenic belt of the Barrovian metamorphic belt series are clearly incompatible with this model of heat supply. Multiple episodes of thermal activity in the Barrovian metamorphic belt ([Ague & Baxter, 2007](#); [Viète et al., 2011](#)) document localized thermal “disequilibrium” within the crust rather than crustal-scale thermal return to equilibrium, and therefore the source of heat must be the result of repetitive, rapid episodic thermal advection within the crust. In addition, for the source of heat for the formation of Buchan metamorphic series of high-temperature, low-pressure metamorphic belts, [England and Thompson \(1984\)](#) showed that normal thermal models do not

lead directly to a field metamorphic gradient in low-pressure facies series in nature. An additional source of heat is necessary to form such a thermal gradient, and this source can only be magma. The conventional view is that the heat supply of magma in the crust may be related to mechanisms such as lower crustal dismantling and sinking, upwelling of the soft rheosphere, ocean ridge subduction, and mantle column activity (Harley, 2008; Guo et al., 2012; Zheng & Chen, 2017). However, these mechanisms of magma formation are clearly inconsistent with the distribution of magmas or melts (Zhang & Zhang, 2024b). Based on field observations, gabbro intrusion in the Grampian orogenic belt is located within the mid-crust while providing a heat source for Barrovian and Buchan metamorphism (Fettes, 1970; Ashworth, 1975). The output of gabbro is closely associated with the most advanced metamorphism (including mixed petrogenesis), and its output should have been a major heat source for metamorphism. In the Grampian orogeny, the close spatial and temporal relationship between bimodal magmatism and epithermal metamorphism suggests that the metamorphism was caused by heat flow from the lower crust or mantle to the mid-crust and was a large-scale contact metamorphism (Ren et al., 2018), implying that the heat of metamorphism may have originated from magma and related fluids (Baxter et al., 2002). This is fully consistent with the mechanism in this paper.

### 3.2. Formation of Overpressure

From the previous analysis, it can be seen that in the orogenic belt, due to the existence of the arch tectonic effect, the internal pressure of the lithosphere below the middle and lower crust is not equal to its lithostatic pressure, but rather, a low-pressure environment is formed in some areas while an overpressure environment is formed in other areas. The factors that contribute most to the formation of overpressure are: 1) circumferential stress formed by arch tectonics. In the orogenic belt, the crust is thicker, such as the thickness of the crust along the Himalayas is about 75 km. According to hydrodynamics, the lithostatic pressure is about  $P = \rho gh$ , substituting  $\rho = 2670 \text{ kg/m}^3$  (the average density of the mountain),  $g = 9.8 \text{ m/s}^2$  (the acceleration of gravity), and  $h = 75 \text{ km}$  into this equation gives  $P = 2 \text{ GPa}$ . Due to the effect of arch tectonics, the overlying lithostatic pressure is not simply equal to the gravity of the overlying rock mass, and in some areas (e.g., near the roots of basins), the static rock pressure is much higher than the gravity of the overlying rocks (Zhang & Zhang 2024a, 2025), up to several times. Thus, beneath the crust of the Himalayan margin, the pressure may be much greater than 2 GPa due to arch tectonics. 2) Thermal pressure. Chen (2005) concluded that under the lithospheric pressure and isotropic elasticity conditions of 15 - 20 km in the middle and upper part of the crust, the thermal stresses due to the change of temperature by  $100^\circ\text{C}$  are about 100 MPa. Hu et al. (2003, 2008) showed that the pressure gradient in the lithosphere is generally a superposition of the thermopressure (thermal) gradient and the gravity gradient, which is related to the ground temperature, composition, phase, and nature of the system. Influenced

by these factors, the pressure gradient in the lithosphere is significantly higher than the lithostatic pressure gradient, even up to 2 - 4 times the lithostatic pressure gradient. In particular, the thermal pressure coefficient in the lithosphere at the material phase transition point increases dramatically, thus causing a thermal pressure increase or even a localized explosion. 3) System phase change. In a nearly closed environment, the system temperature increase and metamorphism caused by changes in the phase state of substances and changes in the composition of substances, etc., can lead to pressure changes. For example, the volume of water-bearing serpentine increases by 7.78% - 15.56% after dehydration reaction in the temperature region above 500°C, and the volume of talc can increase by 0.72% - 4.12% after dehydration. According to the Preliminary Reference Earth Model (PREM), the adiabatic bulk modulus varies from 127.0 to 131.5 GPa over a range of 24.4 to 220 km, and a 1% increment in volume causes a pressure increment of 1.27 to 1.315 GPa (Anderson, 1993). Another experiment showed that at the melting point temperature of a solid, an 8% increase in the volume of a molten solid can result in a localized pressure increment of the solid of up to 10.16 - 10.52 GPa (Hu et al., 2015). Even in an open environment, an ultrahigh-pressure environment can be formed as long as the rate of pressurization is greater than the rate of pressure release (Wang, 1996). Magmatic activities in the orogenic belt will undoubtedly cause some minerals to undergo dehydration and phase changes, resulting in the formation of UHP metamorphism. In conclusion, the pressure source of UHP metamorphism is not only the static rock pressure, but also the superposition of various pressures. In the orogenic belt, it is easier to form an ultrahigh-pressure environment due to arch tectonics and magmatism. Therefore, ultrahigh-pressure metamorphic rocks can be formed entirely within the Earth's crust.

It is common for previous authors to equate metamorphic pressure simply with lithostatic pressure, an approach that, except in the plastic mantle, may be at variance with reality in the hard lithosphere, especially the crust. Therefore, many researchers have questioned the direct conversion of pressures determined from metamorphic reactions and mineral phase transitions to lithospheric depth (Wang, 1996; Wu & Chi, 2003; Moulas et al., 2014, 2022; Tang & Hou, 2016; Zhou & He, 2017; Chu et al., 2017; Lü et al., 2017, 2024; Putnis et al., 2021). Hu et al. (2015) argued that the total pressure inside the rock system = overlying static rock load pressure + tectonic pressurization + internal phase change pressurization of the system, so the pressure of UHP metamorphism should be composed of 3 parts, such as the overlying static rock load pressure, the tectonic pressurization and the internal phase change pressurization of the system. According to Liu et al. (2017), the UHP is synthesized by gravity, tectonic force and other forces, and thus the tectonic force and other combined forces should be subtracted from the total pressure when calculating the depth from the pressure determined by mineral phase change. Lü et al. (2017) established a "hydrostatic pressure model of gravity-tectonic force composite" based on this discussion, and used this model to project

the depth of Dabie UHP metamorphic rock formation to be between 23 and 55 km, which is much shorter than the depth of more than 100 km in the traditional view (Shen et al., 2018; Zhang et al., 2021a). Obviously, these researchers all agree that tectonic stress has an important role in the formation of overpressure. The mechanism in this paper further clarifies the main source of tectonic stress in the orogenic belt.

### 3.3. Formation of Paired Metamorphic Belts and the Intrinsic Connection between the Various Types of Metamorphism

Paired metamorphic belts refer to two metamorphic belts with different pressure types or metamorphic facies that are roughly parallel to each other, a concept first proposed by the Japanese geologist Miyashiro (1961). He believed that the Pacific Rim region and many metamorphic areas in the world usually consist of a paired metamorphic belt composed of a low-pressure belt (or low P/T-type metamorphic belt) on the continental side and a high-pressure belt (or high-P/T-type metamorphic belt) on the oceanic side, and the formation periods of the two are the same or close to each other. The formation mechanism is as follows: in a plate subduction to the other plate below, along the subducting plate side, due to the higher pressure, the plate is colder, and a high-pressure, low-temperature metamorphic belt is usually formed; the symbol mineral is glaucophane, and on the ascending plate side, due to the magma produced by subducting plate erosion, low-pressure, high-temperature metamorphic belts are usually formed, and the symbol mineral is andalusite. As a result, paired metamorphic belts are usually exposed in pairs at convergent plate margins (Zheng & Chen, 2017; He & Zheng, 2019; Zhang et al., 2021b). However, based on the temperature-pressure gradient-to-depth relationship conversion, glaucophane forms at a depth of about several tens of kilometers, whereas andalusite forms at a depth of less than a few kilometers or even shallower. So, we have to ask, why are minerals with a difference of several tens of kilometers in formation depth always exposed at the same time? If it is caused by exhumation, what is the mechanism? This cannot be explained by the theory of subduction (Zhou et al., 2020). In the mechanism of this paper, the formation of double metamorphism is not a difference in the depth at which the minerals are located, but rather a difference in location; the high-temperature, low-pressure metamorphic belt in the belly of the mountain range and the low-temperature, high-pressure metamorphic belt at the edge of the mountain range are at roughly the same depth, and so the paired metamorphic belts are usually capable of being exposed at the same time.

In fact, in many orogenic belts, not all are such double metamorphic pairs; multiple metamorphisms coexist. For example, a medium-temperature, medium-pressure Barrovian metamorphic belt and a high-temperature, low-pressure Buchan metamorphic belt (Zheng et al., 2004; Kohn, 2014; Zhang et al., 2019), as well as a low-temperature, high-pressure Alpine metamorphic belt (Wang et al., 2017; Li et al., 2018; Zhang et al., 2019), exist in the Himalayan orogenic belt, and the various

metamorphisms are superimposed, intertwined, and even inverted. The Grampian Massif at the southern margin of the Scottish Highlands is a classic Barrovian metamorphic series outcrop area, with a typical “medium isothermal pressure gradient P/T” metamorphic series, while the Buchan metamorphic belt is located to the north of the Barrovian metamorphic belt (Ren et al., 2018); the Barrovian metamorphic belt and the Buchan metamorphic belt can share the sillimanite belt. The Grampian orogeny in western Ireland produced high-pressure glaucophane schist-phase metamorphism (–1.0 GPa) (Chew et al., 2003; Sawaki et al., 2010). For these intricate metamorphisms, subduction does not provide a good explanation. In the mechanism of this paper, the intrinsic connection of various types of metamorphism is very clear and readily apparent (Figure 2). Of course, not all orogenic belts have three types of metamorphic facies, due to the fact that the migration of magma is affected not only by arch tectonic stress but also by crustal fractures or fissures, which leads to the migration route and intrusion of magma into an area far away from high-pressure or medium-pressure zones, resulting in the high-pressure or medium-pressure zones, due to the lower temperature, not undergoing metamorphism, and thus a type of metamorphic facies series is missing.

#### 4. Conclusions

This paper proposes a mechanism for the formation of the temperature and pressure required for metamorphism within the crust. Due to the arch tectonic effect, the stress below the mountain range belly is much lower than that below the two edges of the mountain range, so that low- and high-pressure regions are formed in the mountain range belly and the mountain range edge, respectively. At the same time, magma originating from the mantle and the asthenosphere, after entering the Earth’s crust along cracks or fissures, converges from the high-stress mountain range edge to the low-stress mountain range hinterland, thus creating low- and high-temperature environments at the mountain range edge and hinterland, respectively. As a result, high-pressure (low T/P value) and low-pressure (high T/P value) metamorphisms were generated at the edge of the mountain range and the belly of the mountain range, respectively, while medium-pressure (medium T/P value) metamorphisms were generated in the intermediate area between the edge of the mountain range and the belly of the mountain range. Therefore, the temperature and pressure of metamorphism in orogenic zones are not controlled by depth, but are closely related to arch tectonic effects and magmatic activity. Of course, the mechanism proposed in this paper, which is only a qualitative theoretical description at present, needs to be proved by data simulation and tested experimentally. This is also the direction and focus of the next research.

#### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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