Scientific Research Publishing

Open Journal of Geology, 2025, 15(7), 358-376
https://www.scirp.org/journal/ojg
ISSN Online: 2161-7589
ISSN Print: 2161-7570

Dynamical Mechanisms of Melt Migration Beneath Mid-Ocean Ridges

Mengke Zhang, Guowen Zhang*

Wuhan Neutrino Science & Technology Co., Ltd., Wuhan, China
Email: *gwz1000@sina.com

How to cite this paper: Zhang, M.K. and Zhang, G.W. (2025) Dynamical Mechanisms of Melt Migration Beneath Mid-Ocean Ridges. *Open Journal of Geology*, **15**, 358-376.
https://doi.org/10.4236/ojg.2025.157018

Received: June 10, 2025
Accepted: July 20, 2025
Published: July 23, 2025

Abstract

The mid-ocean ridge serves as the epicenter of oceanic spreading. It generates the majority of the Earth's magmas and is the birthplace of new oceanic crusts. However, our current comprehension regarding the operation of the mantle beneath the mid-ocean ridge and the mechanism of melt migration remains rather hazy. In this paper, by taking into account the geomorphological and tectonic characteristics of the mid-ocean ridge as well as the arch tectonic effect, we put forward a mechanism for the melt migration dynamics of the mid-ocean ridge. Moreover, in combination with the theories of neutrino oscillation-induced decay of radioactive elements and magma formation, we discuss and account for the reasons underlying the formation of mid-ocean ridge dunite channels, new oceanic crusts, and striped magnetic anomalies. This mechanism reveals that the mid-ocean ridge and the ocean basins on either side together form an arch tectonic structure. Through this arch structure, the mid-ocean ridge is capable of transforming the gravity of its rock mass into circumferential stresses and then transferring them to the basins on both sides. As a result, the pressure exerted on the basins is significantly greater than the gravity of their own rock masses, while the force acting on the lower part of the mid-ocean ridge's "abdomen" is much smaller than the gravity of the mid-ocean ridge's rock mass itself. In this manner, within the mantle and asthenosphere beneath the ocean basin - mid-ocean ridge - ocean basin tectonic system, there exists a transverse stress that points from the ocean basin towards the ocean ridge. Meanwhile, the melts originating from the mantle and the asthenosphere possess a substantial vertical upward buoyancy. Under the combined action of these two forces, the melts migrate upward at a certain inclination and eventually converge in the narrow region at the top of the mid-ocean ridge and overflow, giving rise to the formation of new oceanic crusts. Simultaneously, the symmetric distribution of magnetic anomalies on both sides of the mid-ocean ridge is constructed.

Keywords

Mid-Ocean Ridges, Melt Migration Dynamics, Neutrino-Induced Radioactive Decay, Dunite Channels, New Oceanic Crust, Oceanic Striped Magnetic Anomalies

1. Introduction

These mid-ocean ridges are typically regarded as the centers of oceanic spreading, responsible for generating the vast majority of the Earth's magma and serving as the sites where nascent oceanic crust forms. Nevertheless, up to now, the mechanisms through which mantle melts are extracted and then migrate to mid-ocean ridges to create new oceanic crust remain poorly understood [1].

Previous authors have developed a conceptual model of the extraction and migration system of mantle melt at mid-ocean ridges, incorporating experimental petrological and geophysical investigations as well as detailed studies of ophiolites. According to this model, partial melting of the upwelling mantle takes place, and these melts ascend upward via diffuse pore flow. As lava reaction and deformation progress, the melts gradually accumulate within the dunite dike in the deep mantle, forming a network of dunite channel systems that connect the source region of the mantle and the oceanic crust (**Figure 1**). Subsequently, a substantial amount of melts converge in the channel system and migrate to the shallow part of the mantle to rapidly form the oceanic crust [2]-[5]. However, in this melt migration model, there are still many aspects that are rather vague, especially the melt convergence mechanism, which needs further research and improvement. Studies have shown that the width of the deep mantle melting zone is several hundred kilometers [6], and these melts eventually converge to a narrow area of several kilometers at the top of the mid-ocean ridge, where they overflow to form new oceanic crust [7]. Previous studies have proposed various models to explain melt convergence [8], such as ridge suction [9], decompaction layers [10], and melting pressure focusing [11], etc. Although these models have been widely studied and recognized, they still have certain limitations because they discuss the process of melt accumulation from different perspectives [8]. For example, regarding the position of the Lithosphere-Asthenosphere Boundary (LAB) at the mid-ocean ridge, the decompaction layers model is inconsistent with geophysical observation results [8] [11]. The boundary conditions set by the melting pressure focusing model are extremely complex, and the geochemical environment of the mid-ocean ridge may hardly meet such conditions. In addition, experimental petrology reveals that mantle melt compositions are controlled by variations in melt depth. Initial melts of mid-ocean ridge basalts (MORBs) are unable to saturate plagioclase (Opx) at depths of at least 30 km below the top of the mantle, which contrasts with the widespread occurrence of Opx in peridotites in the deep ocean [2] [12]-[14].

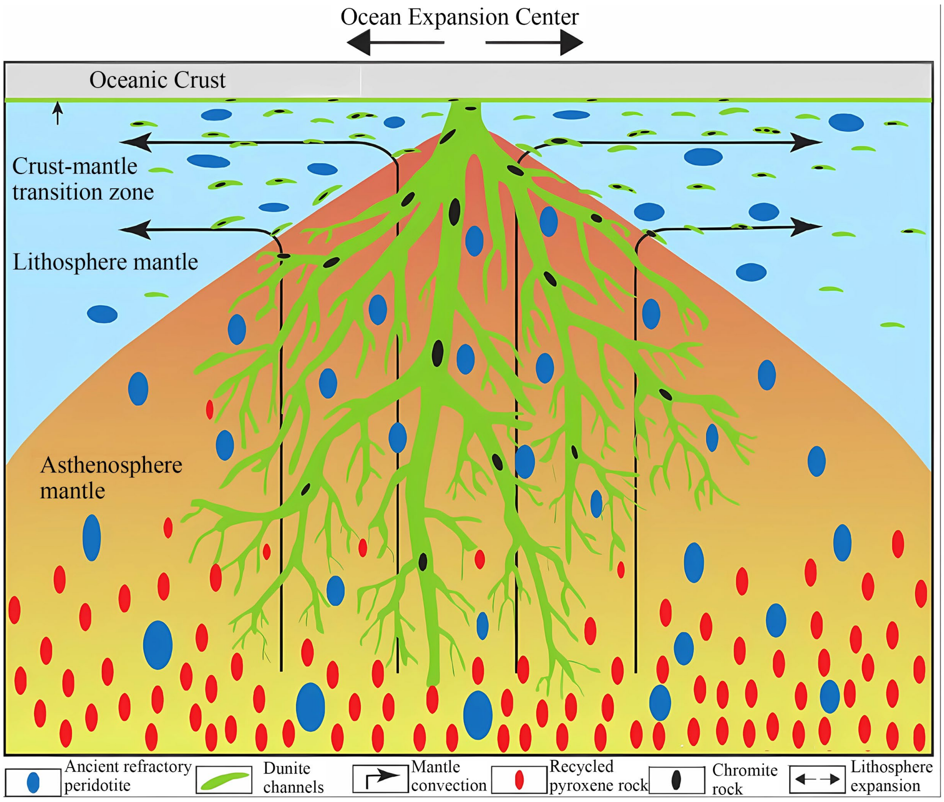

Figure 1. Schematic diagram of the giant magma extraction system in the center of the ocean spreading. (Image quoted from Xiong [5])

In this work, we conduct an analysis of the forces acting on the melt beneath the mid-ocean ridge by relying on the basin-mountain coupled arch-tectonic dynamics model [15] as well as buoyancy effects [16]-[18]. Subsequently, we put forward a dynamical mechanism for the migration of the melt. Furthermore, on the basis of the latest research findings regarding neutrino oscillation-induced radioactive decay and magma formation [19] [20], we explore the formation mechanisms of dunite channels, new oceanic crusts, and striated magnetic anomalies at mid-ocean ridges.

2. Methods

2.1. Arch Tectonic Model of the Mid-Ocean Ridge and Its Force Analysis

Zhang and Zhang [15] put forward an arch tectonic model of basin-mountain coupling during their research on basin-mountain evolution. They contended that in the basin-mountain-basin system, mountain ranges are analogous to a gigantic arch bridge spanning the basins on both sides, thus forming an arch tectonic system. In this system, the mountain range can convert its massive gravity through the arch structure into lateral extrusion pressure (namely, circumferential stress) exerted on the two sides of the basin. As a result, the pressure on the basin is significantly greater than that in the hinterland of the mountain range. It is precisely the stress difference generated by this arch tectonic effect that furnishes the driving force for the subsidence of the basin and the uplift of the mountain range. Mid-ocean ridges are submarine mountain ranges, and their formation mechanism is fundamentally the same as that of onshore mountain ranges. The mid-ocean ridge and the ocean basins on both sides of it constitute a typical arch-shaped structure (Figure 2(a)). The lofty mid-ocean ridge resembles a huge "arch bridge" spanning between the two ocean basins, while the two ocean basins on both sides are like the two abutments of the "arch bridge". The force characteristics of the arch structure are as follows: under the action of the vertical load q of the arch structure, the supporting point not only generates the vertical reaction force V but also produces the horizontal thrust H (Figure 2(b)). Owing to the existence of this horizontal thrust, the bending moment of the arch will be much smaller than that of a horizontal beam with the same span. Consequently, the entire arch construction is mainly under compressive stress. If the arch is sufficiently rigid, the entire weight of the arch construction can be transferred to the bases on both sides through circumferential stresses, which will then be borne by the bases, and the stress beneath the arch construction can be as low as 0 [21].

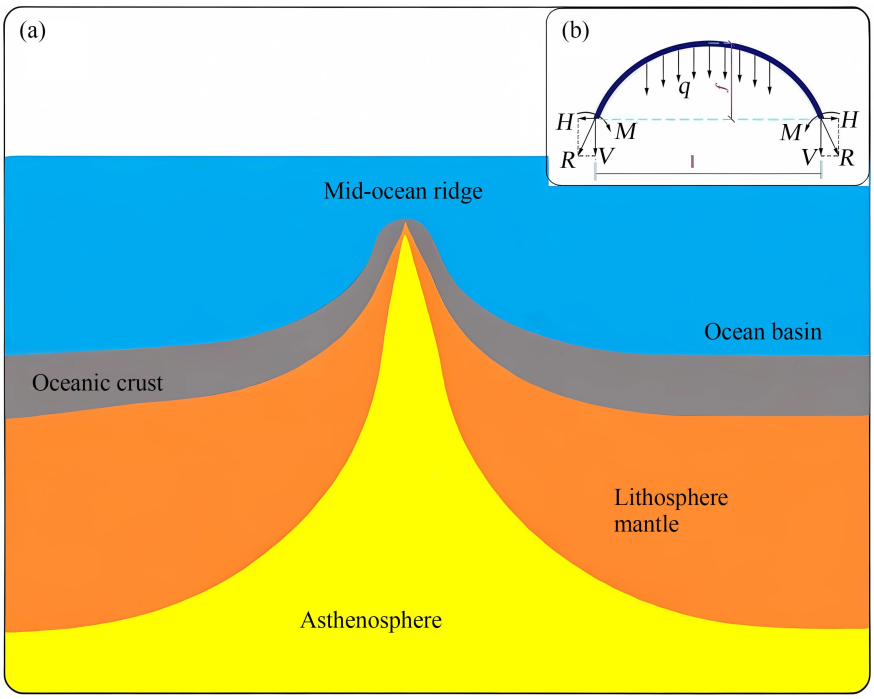

Figure 2. Model of the mid-ocean ridge with arch structure and force analysis. (a): mid-ocean ridge with arch structure; (b): force analysis of arch structure.

For convenience, we can planarize the arch structure and divide it into 4 small pieces (Figure 3(a)), and take any small piece, e.g., piece "1" in Figure 3(a), and analyze the force, it is clear that piece "1" is supported (squeezed) by pieces "2" and "3" on both sides (Figure 3(b)), which remain in equilibrium for the following conditions.

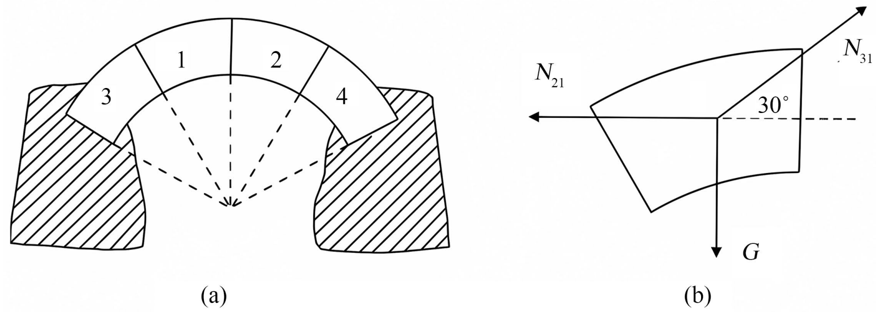

Figure 3. Stress anlaysis of arch structure model. (Image cited in Mao, *et al.* [21])

$$\begin{cases} N_{21} = N_{31} \cos\theta \\ N_{31} \sin\theta = G \end{cases} \tag{1}$$

or

$$\begin{cases} N_{21} = \dfrac{G}{\tan\theta} > G \\ N_{31} = \dfrac{G}{\sin\theta} > G \end{cases} \tag{2}$$

From Equation (2), the lateral stress (*i.e.*, circumferential stress) of an arch is greater than its perpendicular gravitational force. When the arch arc is large, its lateral stresses (N_{21} and N_{31}) are much larger than the gravity (G), *i.e.*, most of the gravity of the arch is converted into lateral stresses.

For the ocean basin - mid-ocean ridge - ocean basin arch tectonic system, the vertical height of the arch is considerably smaller than its lateral span. Such a small curvature might seemingly weaken the role of the arch tectonic structure. However, given that the Earth itself is a near sphere with a certain curvature, which has an amplifying effect on the mid-ocean ridge arch tectonic structure, even if the arc of the ocean basin - mid-ocean ridge - ocean basin arch tectonic structure is rather slight, the mid-ocean ridge arch tectonic structure will still have a highly significant effect. Consequently, despite the small arc of the ocean basin - mid-ocean ridge - ocean basin arch structure, the role of the mid-ocean ridge arch structure remains very significant.

2.2. Analysis of the Force on the Lithosphere and the Asthenosphere of the Mid-Ocean Ridge

The mid-ocean ridge arch structure primarily consists of the lithosphere, which possesses a certain degree of rigidity. The asthenosphere underlying the lithosphere is composed of plastic materials that are prone to flowing or creeping and have difficulty in resisting shear. As a result, the thickness of the arch is basically equivalent to that of the lithosphere. Given that the thickness of the lithosphere is extremely thin compared to the radius of the Earth, it can be regarded as a simple thin layer of the spherical shell in the mechanical structure of the lithosphere, with the lithosphere's own gravity acting as the load on the shell.

For a simple thin spherical shell, the maximum critical elastic buckling load P_α that it can actually withstand can be expressed by the following equation [22]:

$$P_\alpha = 0.84E\left(\frac{\delta}{R}\right)^2 \tag{3}$$

where E represents the Young's modulus of the rock, δ stands for the thickness of the spherical shell, and R is the radius of the spherical shell. Li *et al.* [23] calculated the maximum critical elastic buckling loads that different compositions of the lithosphere can endure based on Equation (3). The findings reveal that the Earth's lithosphere, functioning as a thin spherical shell, can only bear a load of less than 30 MPa. On average, the stress distribution caused by the lithosphere's own gravity is approximately 3 GPa. Consequently, the strength of the lithosphere is far from sufficient to withstand its own gravity. However, the lithosphere usually remains in a state of mechanical equilibrium thanks to the support provided by the underlying asthenosphere. In other words, to guarantee that the lithosphere is not crushed (fractured), the plastic asthenosphere must share at least an average pressure (gravity) of around 3 Gpa - 30 MPa = 2.97 GPa exerted by the overlying lithosphere. Since the Earth's lithosphere is neither uniformly thick nor intact, the forces acting on the asthenosphere beneath the lithosphere vary significantly. Particularly at mid-ocean ridges and their adjacent areas, which feature arch formations, part of the lithosphere's gravity is transferred to the ocean basins on both sides. This leads to a decrease in the actual gravitational force exerted beneath the mid-ocean ridges while increasing the pressure exerted on the basins on either side. Moreover, on average, the thickness of the lithosphere in the ocean basins is about tens of kilometers greater than that of the mid-ocean ridges, and the hydrostatic pressure they bear is approximately 1 to 2 GPa higher than that of the mid-ocean ridges. Therefore, the pressure on the plastic asthenosphere beneath the ocean basin is considerably higher than that beneath the mid-ocean ridge, which will cause the asthenosphere melt to flow from the high-stress ocean basin to the lower-stress area beneath the mid-ocean ridge.

2.3. Buoyancy of Mantle Melts

It has been demonstrated that atmospheric neutrinos can generate MSW (Mikheyev-Smirnov-Wolfenstein) [24] [25] mechanisms as they propagate and oscillate within the Earth by interacting with Earth matter. Zhang and Zhang [19] [20] further emphasized that the MSW mechanism is, in fact, a typical physical resonance. This resonance has a profound impact on the behavior of atmospheric neutrino oscillations, increasing the probability of neutrino flavor conversion. Meanwhile, it also exerts a certain influence on the Earth's matter. It can trigger the unstable radionuclides in the resonance region, boost their decay probability, release more heat, and even cause some of the materials to melt. The melts or magmas originating from the upper mantle and the asthenosphere are produced due to the MSW resonances formed by atmospheric neutrino oscillations, which stimulate radioactive decay and heat generation. A notably distinct feature of this theory regarding the origin of magma, when compared to the theories of magma production through depressurization or volatile fraction injection melting, is that the temperature of the initial melt or magma is typically significantly higher than that of the surrounding rock. Moreover, its temperature and chemical composition are independent of depth. Even at shallow depths, the temperature can be high enough to melt refractory components, provided that sufficient decay heat is generated. Owing to the expansive nature of silicate melts, the volume and structure of the melt expand considerably with increasing temperature [26]. Consequently, once the melt is formed, its density decreases due to volume expansion to a level that is significantly lower than the density of the surrounding rock. As a result, the melt experiences greater buoyancy [16]-[18]. If the densities of both the magma and the surrounding rock are homogeneous, then the buoyancy force exerted by the magma on the viscoelastic or plastic surrounding rock can be expressed as $F = \Delta\rho g V$, where $\Delta\rho$ represents the difference in densities between the magma and the surrounding rock, g is the gravitational acceleration, and V is the volume of the magma [18].

3. Results and Discussion

3.1. Dynamical Mechanisms of Mantle and Asthenosphere Melt Migration at Mid-Ocean Ridges

The melt or magma produced in the mantle and asthenosphere will be subjected to two main forces: a lateral stress ($\boldsymbol{F_x}$) pointing from the ocean basin to the mid-ocean ridge, created by arch tectonic effects and uneven lithospheric thickness, and a vertically upward buoyant force ($\boldsymbol{F_y}$). Under the combined effect of these two forces ($\boldsymbol{F = F_x + F_y}$), the melt or magma is transported upward from the mantle and the asthenosphere at a certain inclination and converges towards the top of the mid-ocean ridge (**Figure 4**). Notably, this mechanism imposes fewer complex boundary constraints and demonstrates greater conceptual simplicity compared to previous models such as melting pressure focusing [9]-[11]. Additionally, the proposed mechanism's description of melt attraction by the low-stress region formed via arch structures offers a more transparent mechanical framework than the ridge suction model presented in prior studies [9]. However, a critical limitation of this mechanism is that its melt-source hypothesis remains untested. When considered in isolation, the mechanism does not explicitly address the melt origin—whether via "neutrino oscillations perturbing radiogenic heat generation" [20], volatile injection, or decompression melting—all of which are thought to converge at mid-ocean ridges under buoyancy and transverse stress effects. Yet, when integrated with the "neutrino oscillations perturbing radiogenic heating" theory [20], the mechanism reveals a coherent process for melt formation and migration. This integrated framework elucidates the genesis of asthenosphere, LAB, seamounts, dunite channels, and new oceanic crust (including oceanic core complexes). As such, extending the proposed mechanism enables it to explain a broader spectrum of geological phenomena than competing models.

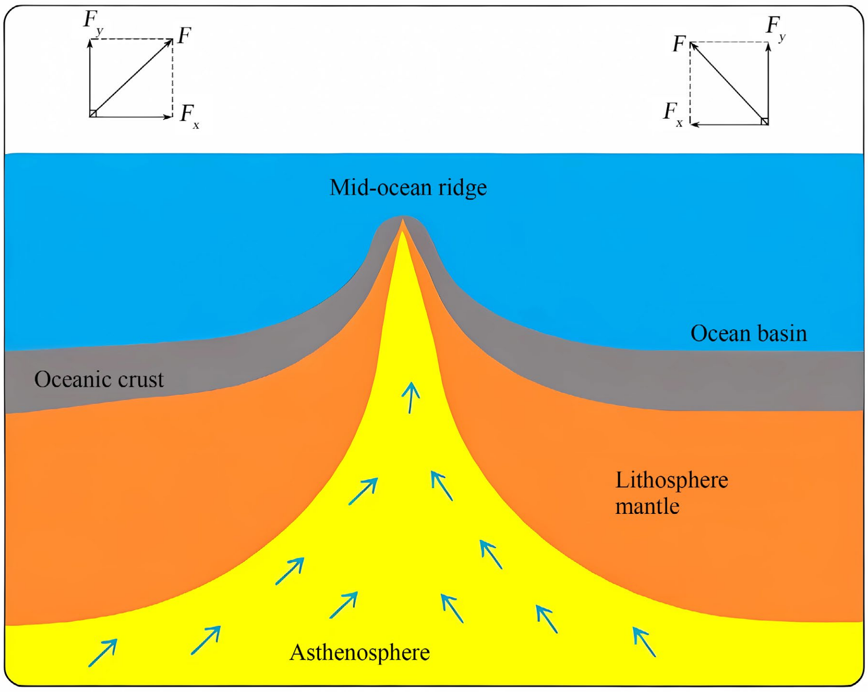

Figure 4. Melts stresses and migration directions below the mid-ocean ridge.

3.2. Formation of Dunite Channels

It has been proposed that the melt migrates within the mantle primarily through two modes: widespread diffuse intergranular porous flow and localized focused channel flow [5]. The former mainly takes place in the deep source regions where mantle melting occurs with low melt/rock ratios, as well as in the non-channelized areas of the shallow mantle. In contrast, the latter occurs within the dunite channels in the mantle. The dunite channel (e.g., **Figure 1**) serves as a passageway for the rapid migration of deep melts towards the shallow oceanic crust [2] [12]-[14]. This channel represents a melt extraction and migration model put forward by previous researchers based on in-depth studies of dunite dikes preserved in ophiolites [2] [27]. The main primary minerals in mantle dunite dikes include olivine (Ol) and a small amount of spinel (Sp), along with occasional pyroxene and sulfides, etc. [5]. It is widely acknowledged that the core process in the formation of dunite dikes is the reaction between silica-unsaturated melts originating from the deep mantle and pyroxene, which generates silica-rich melts and olivine (Melt1 + Opx/Cpx → Melt2 + Ol). This reaction increases the mass of the resultant melts (Melt2) compared to the reactant melts (Melt1), thereby enhancing the porosity of the product peridotites and facilitating the accumulation of surrounding melts into the peridotites [2]. We hold the view that since the upper mantle and the asthenosphere are compositionally heterogeneous [28], it is improbable that melts from the asthenosphere would react with surrounding rocks of diverse compositions at different depths to yield dunite with essentially the same composition. Consequently, there must be another mechanism responsible for the formation of dunite channels aside from the lava reaction. Moreover, this mechanism should also be closely associated with the processes of melt formation and upward transport.

Based on the theory regarding neutrino oscillation-induced radiogenic heat generation and magma formation [19] [20], the melts generated in the mantle are typically distributed randomly and discontinuously. This is due to the probability associated with neutrino oscillations and radioactive decays, along with the heterogeneity in the distribution of mantle radioactivity. These randomly and sporadically distributed melts are gradually transported upwards and accumulate beneath mid-ocean ridges under the influence of buoyancy and lithospheric stresses. The process through which high-temperature melt or magma ascends via rock interstices by osmosis also represents its continuous evolution. During this process, magma exchanges materials and energy with the surrounding environment through melting, extraction, metasomatism, alteration, and dissolution. Moreover, as heat is released and the temperature drops, it crystallizes and precipitates minerals that are compatible with the environmental temperature and pressure [20]. Generally speaking, the melt content in the upper mantle and its asthenosphere is quite low, meaning that they both have low melt/rock ratios. As a result, the melts mainly continue to migrate by infiltration in the form of diffuse intergranular pore flows. Initially, the mantle had a uniform and low temperature. As the magma percolated upwards, it heated the minerals along its path, melted or extracted some low-melting-point medium-acidic or even basic minerals, while precipitating refractory ultrabasic or basic minerals. Consequently, over time, some of the routes where more melt flows became high-temperature basal or ultramafic channels for melt migration. Occasionally, some of the melt might have a lower initial temperature and completely solidify during its journey, forming acidic minerals that block the channel. However, when subsequent high-temperature melt passes over these acidic minerals, it melts and removes these low-melting-point minerals, leaving behind ultramafic or basal minerals like dunite. It is imaginable that through such repeated heating actions, the longer the channel transports the melt, the smaller the temperature difference between the deep and shallow channels becomes. With an increase in the amount of melt and an accelerated transport rate, the temperatures of the deep and shallow channels may eventually be nearly identical. Thus, in this high-temperature channel where the upper and lower temperatures are basically the same, apart from the dunite that remains and recrystallizes in the rising melt, the other basic and acidic components are melted into the melt and migrate to the oceanic crust together, thereby forming a dunite channel. Given that the temperature of the deep channel is almost the same as that of the shallow channel, it is unsurprising that orthopyroxene (Opx) is widely present in seafloor peridotites [2] [12]-[14].

3.3. Formation of New Oceanic Crust at Mid-Ocean Ridges

Based on geophysical probes and studies of paleo-oceanic crust (ophiolite), it is widely held that the top-down layering sequence of the current oceanic crust can be roughly divided into the following: sedimentary layers, extruded basalts (pillow lavas), dykes, gabbros, and peridotites (**Figure 5**) [29] [30]. According to the traditional theory, this layered structure of the oceanic crust can only be formed within the magma chamber. The crystallized gabbro and peridotite precipitate to the lower part of the magma chamber, while the remaining melt floats upward to the upper part of the magma chamber to form dykes and pillow lava. However, geophysical exploration has revealed that there is no such large magma chamber beneath the present-day mid-ocean ridges; instead, only some small and scattered magma-like chambers exist [29]. Consequently, some scholars have abandoned the traditional view regarding large magma chambers and have put forward several new models for the formation of oceanic crust [29] [31]. Nevertheless, all of these new models also have various flaws.

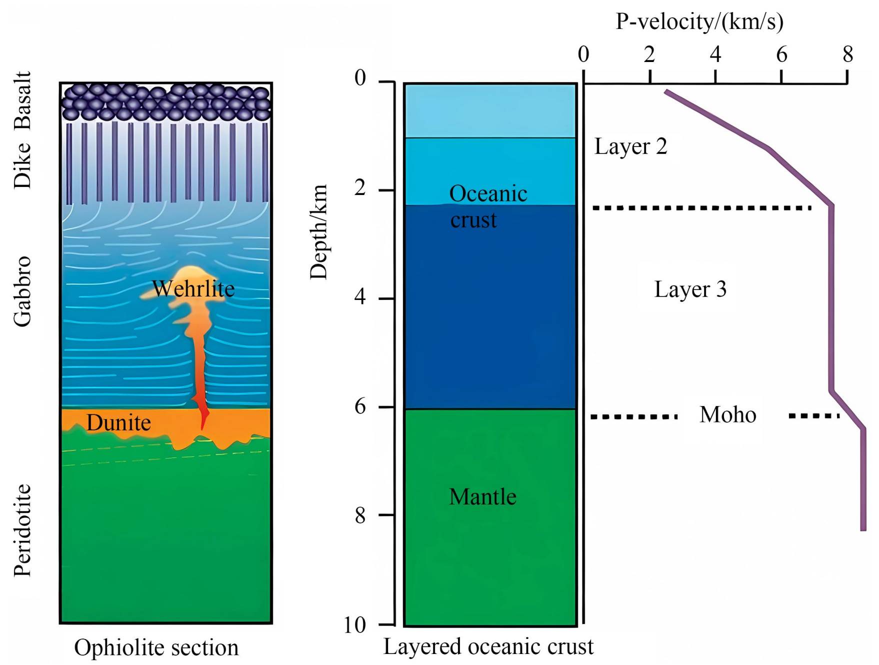

Figure 5. Penrose model of oceanic crust based on Oman ophiolite and its comparison to seismic data. (The image is quoted from Zhou [29]).

In the mantle and the asthenosphere, in addition to the dunite channels, there are regions where some magma migrates as diffuse intergranular pore flows, some of which enter the dunite channels in close proximity and some of which rise outside the dunite channels. However, this form of migration is slow and discontinuous, and therefore does not equalize the temperature in the regions through which the magma migrates, *i.e.*, there are still significant geothermal gradients in these regions. The temperature gradient is larger in the deep, broad mantle regions where magma is scarce, and the closer to the top of the mid-ocean ridge, the more concentrated the magma is, and the temperature gradient is smaller. Therefore, except for the narrow area at the top of the mid-ocean ridge where small magma chambers may be formed, there is usually no large amount of magma converging away from the mid-ocean ridge to form magma chambers. Thus, away from the mid-ocean ridge region, magma migration and evolution can be strongly modulated by geothermal temperature gradients. Compared with the crust, the mantle is usually high-temperature, and after a long period of penetration of the rising magma to melt and clean up, only high-temperature-resistant peridotite can remain. At the same time, rising magma in the mantle can only precipitate high-temperature-resistant peridotite, so that during geological periods, relatively single high-temperature resistant ultrabasic peridotite was formed in the mantle through melt flow, infiltration, and removal. When the magma rises to the oceanic crust, which is sufficiently rigid, the magma can no longer migrate by osmosis and is trapped between the mantle and the oceanic crust, where it continues to converge. As more magma converges and cools, it crystallizes and precipitates some minerals. The first to precipitate, peridotite, sinks to the bottom and becomes part of the mantle, while the gabbro, which crystallizes later, piles up on top of the peridotite and becomes the lower oceanic crust. The residual magma rose to the top and continued to diapir and heat the overlying oceanic crust. At this time, under the action of the overlying low-temperature seawater and the underlying high-temperature magma, the oceanic crust was ruptured by large thermal stresses and numerous cracks were formed, so the magma reached the cold sedimentary layer along the cracks and solidified rapidly into pillow basalt or glassy material, and the cracks were filled with magma to form a dikes (**Figure 5**).

3.4. Formation of Distribution of Striped Magnetic Anomalies on Both Sides of Mid-Ocean Ridges

The magnetic structure of the oceanic crust can be divided into four basic units from top to bottom: ejected basalts, dykes, gabbro, and peridotite (e.g., **Figure 5**) [29]. The uppermost basalt layer mainly consists of pillow lavas with stable strong remanent magnetism compared to the induced magnetization component, and is the main source of shallow seafloor magnetic anomalies [32]-[34]. Talwani *et al.* [35] have developed a model of seafloor magnetic anomaly strips considering topographic variations, and concluded that the seafloor magnetism is mainly originated from the pillow lavas and massive magma flows comprising the ejecta layer of the seafloor crust, and that the dykes or intrusive rocks comprising the seafloor crust do not contribute to the magnetic anomalies. Other models [33] also suggest that the upper layers of predominantly fast-cooling basalts are the main magnetic source of seafloor magnetic anomalies. Thus, the so-called mid-ocean ridge magnetic anomalies are actually magnetic anomalies of surface ejected basalts.

Due to the arch tectonic effect, magma originating from the ocean mantle and the asthenosphere, when arriving at mid-ocean ridges, will mostly flow to the low-stress area directly below the arch tectonic structure. The magma converging in the narrow region of the mid-ocean ridges exerts strong thermal pressure on the surrounding rocks due to the volume expansion of the surrounding materials caused by temperature changes [36]. This thermal stress is an elastic stress (*i.e.*, a force that leads to elastic deformation) that will slowly dissipate in high-temperature creep (plastic deformation) [37]. When plastic deformation can abate the stress generated by elastic deformation in time, the surrounding rock can always remain intact without rupture. At this time, due to buoyancy, the magma converging below the mid-ocean ridge squeezes the overlying rocks, causing the mid-ocean ridge to rise and grow fat. When plastic deformation fails to reduce the stress generated by elastic deformation in time, the surrounding rocks will rupture, at which time the magma converging under the mid-ocean ridge will overflow from the oceanic crust along the fracture cracks, and solidify at the top of the ridge to form a pillow-shaped lava (basalt), which will cause the mid-ocean ridge to grow further taller.

At the same time, when magma overflows from the oceanic crust, it may cause the arch structures of mid-ocean ridges to be damaged and collapse, creating depressions in the mid-ocean ridges that further develop into mid-ocean ridge rift valleys. However, as the magma cools and solidifies, the collapsed ridges are repaired and new arch structures are re-established. As the ridge grows taller and fatter, the overall weight of the ridge increases, so the lateral compressive stresses on the ocean basins on both sides of the mid-ocean ridge that are decomposed by the arch tectonic effect increase further, and the magma underneath it is squeezed, causing it to converge further directly under the mid-ocean ridge (arch structure). The convergence of magma once again subjected the surrounding rocks below the mid-ocean ridge to strong thermal stresses, which led to the uplift or rupture of the overlying rocks again, and the converging magma overflowed and solidified again to form the newer oceanic crust, which also caused the mid-ocean ridge to grow further in height. The old oceanic crust that was torn apart was distributed on both sides of the new oceanic crust formed by the upwelling magma in the later stage (**Figure 6** and **Figure 7**). As a result, the highest oceanic crust at mid-ocean ridges is usually the youngest. As a result, the mid-ocean ridge grows higher and higher as a result of long-term magma overflow and solidification. It can be seen that the lowest point (*i.e.*, the foot of the mountain) is the earliest generation of oceanic crusts, and from the lowest point upward, the age of the oceanic crusts is getting younger and younger, to the highest point of the oceanic ridge, the oceanic crusts are the youngest. When these oceanic crusts solidified, they recorded the geomagnetic features (including geomagnetic inversion) at that time, thus forming the symmetrical distribution of magnetic anomalies on both sides of the mid-ocean ridge in bands.

3.5. Formation of Oceanic Detachment Faults and Oceanic Core Complex

Oceanic detachment faults (ODFs) are low-angle normal faults with large, long-activity fault distances that form at or near mid-ocean ridges. Detachment faults are often accompanied by the formation of oceanic core complex (OCC) [38].

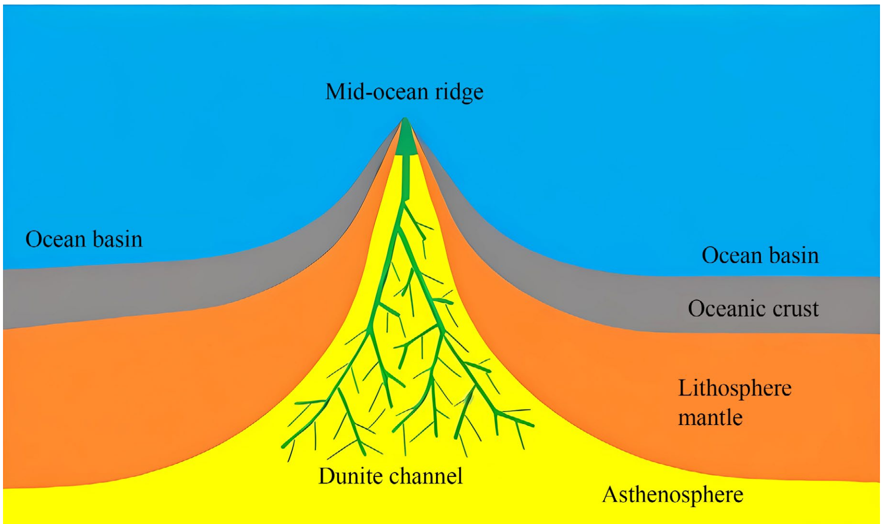

Figure 6. A map of melt convergence at mid-ocean ridges. Mantle melts converge at mid-ocean ridges through dunite channels and spill over.

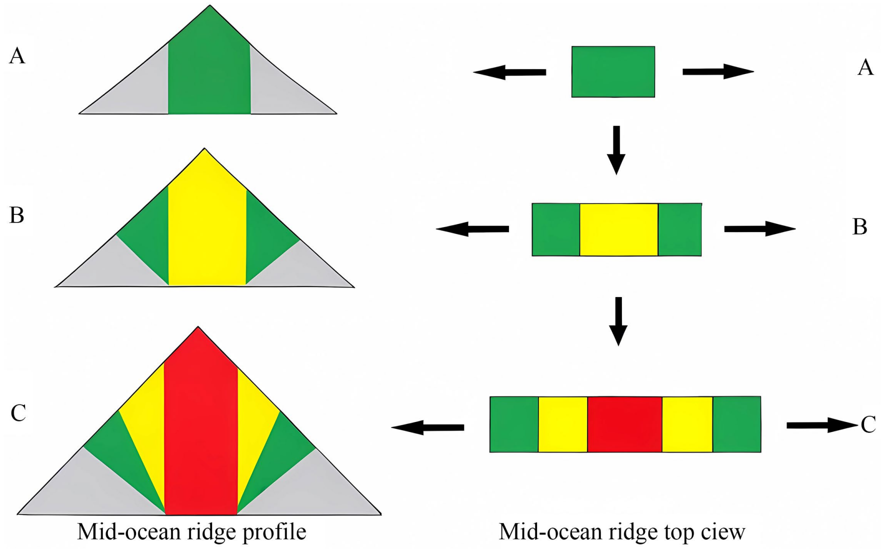

Figure 7. Schematic diagram of the formation of new oceanic crust and striated magnetic anomalies. A, B, and C are the initial, secondary, and latest oceanic ridges, respectively. The green, yellow and red parts are the initial, secondary and latest basalts, respectively.

These detachment faults and OCCs are anomalies in oceanic crust: firstly, their structure lacks the melt, dike and gabbro part of normal oceanic crust, and only the peridotite is exposed directly on the ocean floor; secondly, the magnetization intensity of the rocks does not show a symmetrical distribution, but is characterized by a high degree of anisotropy [39]. These OCCs cannot be explained by the traditional seafloor spreading model, so geoscientists proposed the ocean floor spreading hypothesis of detachment faults, *i.e.*, the Chapman spreading model [40] [41], as a supplement to the old seafloor spreading theory. However, what is the driving force behind the Chapman spreading model? What is the structure and nature of the lithosphere on the other side opposite to the OCC, and how are the Chapman spreading model and the traditional Penrose spreading model temporally and spatially coupled in the mid-ocean ridge section? A series of questions are still very vague and need to be solved by further research [42].

As we have already discussed, mid-ocean ridges sometimes collapse for certain reasons. When the collapse area is large, the mid-ocean ridge arch structure will be damaged, and then the weight of the rock body will not be able to be disassembled and transferred to the two sides of the ocean basin, but rather all the weight will be pressed on the area directly below the ridge, resulting magma beneath the mid-ocean ridge to flow to the sides, and the rocks on the two sides of the ridge will be subjected to huge lateral shear stresses, resulting in the rocks slip and rupture, and the formation of a low-angle detachment faults [41]. If the magma gathered in the belly of the mid-ocean ridge is small, small detachment faults are formed, such as the Gakkel Ridge section in the northern Atlantic Ocean and the easternmost section of the Southwest Indian Ridge; if the magma gathered under the mid-ocean ridge is large, large detachment faults are formed, such as the Mid-Atlantic Ridge [41] [42]. Because of the high temperature on both sides of the magma convergence area below the mid-ocean ridge, and the temperature gradient from top to bottom and from outside to inside, when the magma crystallizes (or when the magma and the surrounding rocks undergo a melt-rock reaction), various kinds of rocks, such as serpentinized peridotite, troctolite, gabbro, diabase and serpentine, are produced. The strong impact of the ridge collapse will cause these pre-existing rocks to crush or collide with each other, and interact with high-temperature magma or plastic materials to form metamorphic rocks dominated by mylonite, chloritization breccias, fault breccias, and fault gouge, etc. [42] [43].

3.6. Issues Related to the Dynamic Mechanism of Seafloor Spreading

As mentioned earlier, the power of the mid-ocean ridge magma to migrate to the seafloor to form new oceanic crust comes from the differential stress formed by the arch tectonic effect of the mid-ocean ridge and the buoyancy of the magma itself. So are these two forces the long-sought driving force for seafloor spreading (*i.e.*, plate movement)? This is an intriguing question. What the mid-ocean ridge arch tectonic effect transmits to the ocean basin is actually circumferential stress, which can be broken down into vertical and horizontal stresses; the vertical stress causes melt to flow from under the ocean basin to the belly of the mid-ocean ridge, while the horizontal stress has a certain squeezing effect on the ocean basin plates. On the whole, the Earth is an approximate sphere, and there are certain circumferential stresses formed by curvature and arch tectonics at any two places on the surface. Mao *et al.* [21] have estimated the circumferential stress of the Earth, which is about 900 MPa at a depth of 20 km, and the authors believe that this stress is sufficient to drive plate motion. Theoretically, the Earth's circumferential stresses can indeed drive plate motion, but in practice, there may be a variety of factors that prevent circumferential stresses from being transmitted over long distances. 1) Rocks all have a certain degree of elasticity and plasticity, and their elasticity enables stress to be transmitted down, while their plasticity consumes the stress [37], deforming the rock or converting the circumferential stress into a driving force for rock uplift or subsidence. If the stress is continuously consumed, it cannot be transmitted to the far side. 2) Since all mountain ranges have arch tectonics [15], the circumferential stress transmitted by the mid-ocean ridge is difficult to be transmitted if it encounters the circumferential stress formed by other mountain ranges (e.g., island arcs, continental mountain ranges, etc.), in which case the rock will either heat and deform or rupture to produce earthquakes, which will cause the circumferential stress to be consumed. 3) Rock slip to form detachment faults also deplete stresses and prevent them from being transmitted down. 4) Subduction depletes circumferential stresses. If all the circumferential stresses are consumed by subduction, then plate motion can continue. However, it is doubtful whether subduction exists [44]. However, since the magma overflow at mid-ocean ridges is the largest and produces a larger volume of new oceanic crust, and thus the lateral extrusion formed by the increase in oceanic crust volume cannot be ignored, it is worthwhile to further investigate whether the stresses generated by the arch tectonic effect of mid-ocean ridges and the extrusion pressure formed by magma solidification can drive seafloor spreading.

4. Conclusion

We propose a mechanism for the focusing of melt beneath mid-ocean ridges. The mechanism states that the arching structure of mid-ocean ridges can create differential stresses on the ridge and its sides. The magma originating from the ocean mantle and the asthenosphere, under the differential stress formed by the arch tectonic effect and the buoyancy of the magma itself, gradually rises from the vast ocean mantle to converge right below the mid-ocean ridge and overflow upward, and ultimately solidify to form a new oceanic crust, resulting in the mid-ocean ridge growing taller and fatter. When the overflowing magma solidified to form basaltic oceanic crust, it recorded the geomagnetic information of the time. After repeated magma overflows and solidification, a symmetrical distribution of magnetic anomalies was formed on both sides of the mid-ocean ridge. At the same time, due to the long-term convergence and migration of magma, a high-temperature channel, *i.e.*, a dunite dike, was formed in the upper mantle, where only refractory peridotite could exist. The dynamical mechanism proposed in this paper is currently only a qualitative theoretical description, which requires further in-depth research and refinement. In further research, the focus should be placed on the following two aspects: 1) the proposed construction of a 2D or 3D finite element modeling system to simulate the melt paths and compare the results with the known data; 2) the validation of the conclusions obtained by the mechanism through geophysical exploration, such as measuring the stresses in the oceanic crust at the top, waist and bottom of the mid-ocean ridges, respectively, in order to verify the stress differentials formed by the arch tectonics, and so on.

Conflicts of Interest

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

References

[1] Katz, R.F., Jones, D.W.R., Rudge, J.F. and Keller, T. (2022) Physics of Melt Extraction from the Mantle: Speed and Style. *Annual Review of Earth and Planetary Sciences*, **50**, 507-540. https://doi.org/10.1146/annurev-earth-032320-083704

[2] Kelemen, P.B., Hirth, G., Shimizu, N., Spiegelman, M. and Dick, H.J. (1997) A Review of Melt Migration Processes in the Adiabatically Upwelling Mantle beneath Oceanic Spreading Ridges. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, **355**, 283-318. https://doi.org/10.1098/rsta.1997.0010

[3] Kohlstedt, D.L. and Holtzman, B.K. (2009) Shearing Melt Out of the Earth: An Experimentalist's Perspective on the Influence of Deformation on Melt Extraction. *Annual Review of Earth and Planetary Sciences*, **37**, 561-593. https://doi.org/10.1146/annurev.earth.031208.100104

[4] Liu, B. and Liang, Y. (2019) Importance of Permeability and Deep Channel Network on the Distribution of Melt, Fractionation of REE in Abyssal Peridotites, and U-Series Disequilibria in Basalts beneath Mid-Ocean Ridges: A Numerical Study Using a 2D Double-Porosity Model. *Earth and Planetary Science Letters*, **528**, Article ID: 115788. https://doi.org/10.1016/j.epsl.2019.115788

[5] Xiong, Q. (2021) Ophiolitic Records of Melt Migration Processes in Oceanic Mantle. *Bulletin of Mineralogy Petrology and Geochemistry*, **40**, 999-1011. https://doi.org/10.19658/j.issn.1007-2802.2021.40.043

[6] Carbotte, S.M., Smith, D.K., Cannat, M. and Klein, E.M. (2015) Tectonic and Magmatic Segmentation of the Global Ocean Ridge System: A Synthesis of Observations. *Geological Society, London, Special Publications*, **420**, 249-295. https://doi.org/10.1144/sp420.5

[7] Forsyth, D.W., Webb, S.C., Dorman, L.M. and Shen, Y. (1998) Phase Velocities of Rayleigh Waves in the MELT Experiment on the East Pacific Rise. *Science*, **280**, 1235-1238. https://doi.org/10.1126/science.280.5367.1235

[8] Sim, S.J., Spiegelman, M., Stegman, D.R. and Wilson, C. (2020) The Influence of Spreading Rate and Permeability on Melt Focusing Beneath Mid-Ocean Ridges. *Physics of the Earth and Planetary Interiors*, **304**, Article ID: 106486. https://doi.org/10.1016/j.pepi.2020.106486

[9] Spiegelman, M. and McKenzie, D. (1987) Simple 2-D Models for Melt Extraction at Mid-Ocean Ridges and Island Arcs. *Earth and Planetary Science Letters*, **83**, 137-152. https://doi.org/10.1016/0012-821x(87)90057-4

[10] Keller, T., Katz, R.F. and Hirschmann, M.M. (2017) Volatiles Beneath Mid-Ocean Ridges: Deep Melting, Channelised Transport, Focusing, and Metasomatism. *Earth and Planetary Science Letters*, **464**, 55-68. https://doi.org/10.1016/j.epsl.2017.02.006

[11] Turner, A.J., Katz, R.F., Behn, M.D. and Keller, T. (2017) Magmatic Focusing to Mid-Ocean Ridges: The Role of Grain-Size Variability and Non-Newtonian Viscosity. *Geochemistry, Geophysics, Geosystems*, **18**, 4342-4355. https://doi.org/10.1002/2017gc007048

[12] Stolper, E. (1980) A Phase Diagram for Mid-Ocean Ridge Basalts: Preliminary Results and Implications for Petrogenesis. *Contributions to Mineralogy and Petrology*, **74**, 13-27. https://doi.org/10.1007/bf00375485

[13] Morgan, Z. and Liang, Y. (2003) An Experimental and Numerical Study of the Kinetics of Harzburgite Reactive Dissolution with Applications to Dunite Dike Formation. *Earth and Planetary Science Letters*, **214**, 59-74. https://doi.org/10.1016/s0012-821x(03)00375-3

[14] Lambart, S., Laporte, D. and Schiano, P. (2008) An Experimental Study of Focused Magma Transport and Basalt–peridotite Interactions beneath Mid-Ocean Ridges: Implications for the Generation of Primitive MORB Compositions. *Contributions to Mineralogy and Petrology*, **157**, 429-451. https://doi.org/10.1007/s00410-008-0344-7

[15] Zhang, G.W. and Zhang, M.K. (2024) Dynamics Model of Arch Structure for Basin-Mountain Evolution. *Gansu Geology*, No. 3, 1-6. https://gsdz.gsdkj.net/ch/reader/view_abstract.aspx?file_no=20240301&flag=1

[16] Roper, S.M. and Lister, J.R. (2005) Buoyancy-Driven Crack Propagation from an Over-Pressured Source. *Journal of Fluid Mechanics*, **536**, 79-98. https://doi.org/10.1017/s0022112005004337

[17] Brown, M. (2013) Granite: From Genesis to Emplacement. *Geological Society of America Bulletin*, **125**, 1079-1113. https://doi.org/10.1130/b30877.1

[18] Sigmundsson, F., Pinel, V., Grapenthin, R., Hooper, A., Halldórsson, S.A., Einarsson, P., *et al.* (2020) Unexpected Large Eruptions from Buoyant Magma Bodies within Viscoelastic Crust. *Nature Communications*, **11**, Article No. 2403. https://doi.org/10.1038/s41467-020-16054-6

[19] Zhang, G.W. and Zhang, M.K. (2024) Research on Neutrino Oscillation-Induced Radioactive Decay. *Modern Physics*, **14**, 135-144. https://doi.org/10.12677/mp.2024.144016

[20] Zhang, G. and Zhang, M. (2024) Effects of Matter in Atmospheric Neutrino Oscillations and the Formation of Magma. *Journal of Geoscience and Environment Protection*, **12**, 270-287. https://doi.org/10.4236/gep.2024.1212017

[21] Mao, X.P., Lu, L.H., Wang, X.M., Fan, X.J., Geng, T. and Wang, H.C. (2020) Role of Circumferential-Direction Stress in Crustal Movement. *Earth Science Frontiers*, **27**, 221-233. https://doi.org/10.13745/j.esf.2020.1.24

[22] Pan, B. and Cui, W. (2010) An Overview of Buckling and Ultimate Strength of Spherical Pressure Hull under External Pressure. *Marine Structures*, **23**, 227-240. https://doi.org/10.1016/j.marstruc.2010.07.005

[23] Li, X. and He, D.W. (2022) Effect of Magma Solidification under High Pressure on Mechanical State of Lithosphere. *Chinese Journal of High Pressure Physics*, **36**, Article ID: 011203. https://doi.org/10.11858/gywlxb.20210905

[24] Wolfenstein, L. (1978) Neutrino Oscillations in Matter. *Physical Review D*, **17**, 2369-2374. https://doi.org/10.1103/physrevd.17.2369

[25] Mikheyev, S.P. and Smirnov, A.Y. (1989) Resonant Neutrino Oscillations in Matter. *Progress in Particle and Nuclear Physics*, **23**, 41-136. https://doi.org/10.1016/0146-6410(89)90008-2

[26] Dingwell, D.B. and Webb, S.L. (1990) Relaxation in Silicate Melts. *European Journal of Mineralogy*, **2**, 427-451. https://doi.org/10.1127/ejm/2/4/0427

[27] Kelemen, P.B., Braun, M. and Hirth, G. (2000) Spatial Distribution of Melt Conduits in the Mantle beneath Oceanic Spreading Ridges: Observations from the Ingalls and Oman Ophiolites. *Geochemistry, Geophysics, Geosystems*, **1**. https://doi.org/10.1029/1999gc000012

[28] Liu, C., Yang, A., Liu, B. and Liu, T. (2022) Compositional Heterogeneity of the Asthenosphere: Advancement and Implications. *Acta Petrologica Sinica*, **38**, 3712-3734.

https://doi.org/10.18654/1000-0569/2022.12.11

[29] Zhou, H.Y. (2017) Fundamental Questions of Ocean Crust and the Dream for Mohole. *Advances in Earth Science*, **32**, 1245-1252. https://doi.org/10.11867/j.issn.1001-8166.2017.12.1245

[30] Boudier, F. and Nicolas, A. (1985) Harzburgite and Lherzolite Subtypes in Ophiolitic and Oceanic Environments. *Earth and Planetary Science Letters*, **76**, 84-92. https://doi.org/10.1016/0012-821x(85)90150-5

[31] Wu, C., Li, H.B., Yao, Y.J., Zhang, H.D., Liu, D.L. and Wei, J.G. (2022) The Project Mohole: A Review and Prospects. *Acta Geologica Sinica*, **96**, 2657-2669. https://doi.org/10.19762/j.cnki.dizhixuebao.2022237

[32] Gee, J.S. and Kent, D.V. (2007) Source of Oceanic Magnetic Anomalies and the Geomagnetic Polarity Timescale. *Treatise on Geophysics*, **5**, 455-507. https://doi.org/10.1016/b978-044452748-6.00097-3

[33] Cande, S.C. and Kent, D.V. (1976) Constraints Imposed by the Shape of Marine Magnetic Anomalies on the Magnetic Source. *Journal of Geophysical Research*, **81**, 4157-4162. https://doi.org/10.1029/jb081i023p04157

[34] Li, Y.J. and Wei, D.P. (2016) Review of Research on Oceanic Striped Magnetic Anomalies. *Progress in Geophysics*, **31**, 949-959.

[35] Talwani, M., Windisch, C.C. and Langseth, M.G. (1971) Reykjanes Ridge Crest: A Detailed Geophysical Study. *Journal of Geophysical Research*, **76**, 473-517. https://doi.org/10.1029/jb076i002p00473

[36] Chen, S.Z. (2005) Crust Mantle Dynamics and Activated Tectonics (Diwa) Theory. *Geotectonica et Metallogenia*, **29**, 87-98. http://www.ddgzyckx.com/#/digest?ArticleID=341

[37] Chen, Z.A. and Li, M. (2019) Is There Any Rheological Failure for Material Inside Earth Interior Due to Long Time Action at Low Stress? *Progress in Geophysics*, **34**, 1-5. https://doi.org/10.6038/pg2019CC0028

[38] Escartín, J. and Canales, J.P. (2011) Detachments in Oceanic Lithosphere: Deformation, Magmatism, Fluid Flow, and Ecosystems. *Eos, Transactions American Geophysical Union*, **92**, 31. https://doi.org/10.1029/2011eo040003

[39] Mallows, C. and Searle, R.C. (2012) A Geophysical Study of Oceanic Core Complexes and Surrounding Terrain, Mid-Atlantic Ridge 13°N-14°N. *Geochemistry, Geophysics, Geosystems*, **13**. https://doi.org/10.1029/2012gc004075

[40] Dick, H.J.B., Lin, J. and Schouten, H. (2003) An Ultraslow-Spreading Class of Ocean Ridge. *Nature*, **426**, 405-412. https://doi.org/10.1038/nature02128

[41] Yu, X., Chu, F.Y., Dong, Y.H., Li, X.H. and Tang, L.M. (2013) Detachment Fault and Oceanic Core Complex: A New Mode of Seafloor Spreading. *Earth Science*, **38**, 995-1004.

[42] Zhang, W., Liu, C. and Dick, H.J.B. (2020) Evidence for Multi-Stage Melt Transport in the Lower Ocean Crust: The Atlantis Bank Gabbroic Massif (IODP Hole U1473A, SW Indian Ridge). *Journal of Petrology*, **61**, egaa082. https://doi.org/10.1093/petrology/egaa082

[43] Blackman, D.K., Karson, J.A., Kelley, D.S., Cann, J.R., Früh-Green, G.L., Gee, J.S., *et al.* (2002) Geology of the Atlantis Massif (Mid-Atlantic Ridge, 30° N): Implications for the Evolution of an Ultramafic Oceanic Core Complex. *Marine Geophysical Researches*, **23**, 443-469. https://doi.org/10.1023/b:mari.0000018232.14085.75

[44] Zhou, H., Qiu, L. and Yan, D.P. (2020) Is Negative Buoyancy the Primary Force Driv-

ing Plate Motion during the Onset of Subduction? A Discussion on Rock Fracture Mechanics. *Earth Science Frontiers*, **27**, 270-274.
https://doi.org/10.13745/j.esf.2020.1.28