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Research Article

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Magma Generation in the ocean continental transition of the Northern South China Sea Continental Margin and Its Modification of the Crust

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Abstract: Current magma formation mechanisms struggle to explain the complex compositional diversity of magmas in the Ocean–Continent Transition (OCT) of the northern South China Sea (SCS). Drawing on the Mikheyev–Smirnov–Wolfenstein (MSW) mechanism of neutrino oscillation and the latest advances in magma genesis research, this paper analyzes relevant datasets from previous OCT studies in the northern SCS to propose a regional magma formation mechanism, which satisfactorily accounts for both local magmatic diversity and OCT formation. A newly developed magma genesis theory holds that magmas form via material melting driven by radiogenic heat from radioactive nucleon decay, triggered by MSW resonant perturbations of atmospheric neutrino oscillations. On this basis, this study further demonstrates that atmospheric neutrinos can generate MSW resonance inside Earth only if a uniform-density material layer at least 1,500 meters thick exists. As a near-isopycnic medium at Earth’s surface, seawater supports atmospheric neutrino MSW resonance once its depth reaches or exceeds 1,500 meters. Such resonance propagates downward into the underlying crust through inertial coupling, triggering radioactive nucleon decay and heat accumulation in crustal rocks. The resulting crustal heating causes rock alteration and partial melting, further driving continuous crustal compaction and progressive thinning, and ultimately controlling the tectonic evolution of the OCT.

Keywords: Northern South China Sea, Crustal thinning, OCT formation, Neutrino oscillation-induced radioactive decay, Formation of magma¹

1. Introduction

A passive continental margin constitutes a gradual transitional zone between continental and oceanic crust, with widths ranging from tens to hundreds of kilometers. Due to intensive magmatism, the crust within this zone undergoes drastic thinning, and its lithology differs from typical continental and oceanic crust, representing an intermediate endmember; this domain is widely defined as the Ocean–Continent Transition (OCT) [1-6]. The northern margin of the South China Sea (SCS) is a typical passive continental margin. Although the exact width of its OCT remains debated, it is generally regarded as relatively narrow—on the order of tens of kilometers—and corresponds to a domain with

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weakened tectonic activity and intensified magmatism[7-10]. Crustal thickness within the northern SCS OCT decreases progressively from the landward side to the seaward side, reaching ~30 km near the continent and merely ~8 km adjacent to oceanic crust[11,12]. Water depth also increases offshore gradually, ranging from approximately 1,500 m to over 3,000 m [6,8,13-15].

The most diagnostic characteristic of the OCT is that crustal thinning is accompanied by magmatic compensation. This leads to gradual variations in both the lithology and thickness of OCT crust, which ultimately evolves into transitional crust mixed with continental and oceanic crustal components. Accordingly, magmatic activity exerts a pivotal control on OCT formation and the progressive thinning of continental crust [2,10,16].

To date, a wealth of first-hand data on OCT magmas in the northern SCS has been obtained through geophysical imaging, grid sampling, and drilling. Based on these data, geologists have conducted in-depth studies on the origin and deep dynamics of magma within the OCT crust in the northern SCS, proposing various magma genesis mechanisms. These include decompression melting triggered by mantle and asthenospheric material upwelling driven by crustal extension and thinning [10,14,17-19], mantle melting induced by dehydration during plate subduction [20,21], and mantle plume ascent [20,22], among others. However, these magma-forming mechanisms all have certain limitations and cannot fully explain the complex diversity and spatiotemporal distribution of OCT magmas in the northern SCS. For example, decompression melting from mantle upwelling struggles to account for the occurrence of intermediate-acidic rocks and the extremely low Nb/U ratios in the magmas[23,24], while subduction cannot explain enhanced magmatic activity following rifting or extension[22], and mantle plumes fail to account for early-stage magma generation[20,25], among other inconsistencies. In addition, the crust along the northern continental margin of the SCS exhibits multiple heterogeneous structures, such as the low-velocity layer (LVL) at the base of the upper crust, the metamorphic core complex (MCC) within the middle crust, and the high-velocity layer (HVL) in the lower crust; all of these structures are closely linked to magmatic activity [11,18,26-28]. At present, no single mechanism can fully interpret the development of these crustal heterogeneities. Therefore, further reassessment and refinement of magma formation mechanisms and dynamic processes for the northern SCS OCT are critical to deciphering the evolutionary history of the SCS and its northern OCT. In recent years, Zhang and Zhang [29-31] have proposed a novel magma generation mechanism. This mechanism posits that atmospheric neutrino oscillations via the Mikheyev–Smirnov–Wolfenstein (MSW) effect [32-34] trigger the decay of radioactive substances, which partially melts the Earth's interior and generates magma. This study employs this new magma formation mechanism to interpret the origin of OCT magmas beneath the northern SCS and clarify magmatic controls on OCT evolution. Based on the MSW resonance of atmospheric neutrinos, this paper first discusses the

prerequisite conditions for atmospheric neutrinos to undergo MSW resonance inside the Earth's interior, then analyzes how MSW resonance induced by atmospheric neutrinos in seawater alters the underlying crust, and finally establishes a coupled genetic model for magma generation and OCT development within the northern SCS continental margin crust. Additionally, this work accounts for the compositional diversity of northern SCS OCT magmas, the origin of heterogeneous deep crustal structures (including intracrustal LVL, HVL, and MCC), and the occurrence of continental-type granites in oceanic domains.

2. Methods

2.1 MSW Resonance of Atmospheric Neutrinos

Wolfenstein [34] was the first to establish the evolution equations for neutrinos in a medium and studied the material effects of neutrino oscillations. Based on Wolfenstein's evolution equations for neutrinos in matter, Mikheyev and Smirnov [32,33] further derived the conclusion that neutrinos propagating through matter exhibit resonant characteristics, known as the MSW mechanism. For convenience, we will use the two-flavor neutrino oscillation $\nu_e \leftrightarrow \nu_\mu$ as an example for a brief explanation. Neutrino conversion can be described using the instantaneous eigenstates ν_{1m} and ν_{2m} of the Hamiltonian in matter. By representing any neutrino state as $|\nu\rangle = \psi_{1m}|\nu_{1m}\rangle + \psi_{2m}|\nu_{2m}\rangle$, the evolution equation for neutrinos propagating in matter can be written in terms of (ν_{1m}, ν_{2m}) [35]:

$$i \frac{d}{dt} \begin{pmatrix} \psi_{1m} \\ \psi_{2m} \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m_m^2}{4E} & -i \frac{d\theta_m}{d\chi} \\ i \frac{d\theta_m}{d\chi} & \frac{\Delta m_m^2}{4E} \end{pmatrix} \begin{pmatrix} \psi_{1m} \\ \psi_{2m} \end{pmatrix} \quad (1)$$

Here, θ_m is called the matter-effect mixing angle, and Δm_m^2 is the effective mass difference. Their relationship with other parameters is given by:

$$\Delta m_m^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2} \quad (2)$$

$$\frac{d\theta_m}{d\chi} = \frac{1}{2} \cdot \frac{\sin 2\theta_m}{\Delta m_m^2} \frac{dA_{CC}}{d\chi} \quad (3)$$

In the above equations, E is the neutrino energy, θ is the mixing angle in vacuum, $\Delta m^2 = |m_2^2 - m_1^2|$ is the difference in the squares of the masses of the

two mass eigenstates, and $A_{CC} \equiv 2EV_{CC} = 2\sqrt{2}EG_F N_e(\chi)$ (where G_F is the Fermi constant, $N_e(\chi)$ is the electron number density in matter, and V_{CC} is the effective potential). If the medium density is constant, solving Equation (1) yields the conversion probability from ν_e to ν_μ as:

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2 2\theta_m \sin^2 \left(\frac{\Delta m_m^2 L}{4E} \right) \quad (4)$$

When the neutrino energy and matter density (electron number density) satisfy the following relationship, neutrino resonance occurs (i.e., the MSW mechanism is activated):

$$N_e = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F E} \quad (5)$$

At resonance, neutrino mixing can reach its maximum even if the mixing angle in vacuum is small.

2.2 Necessary Conditions for MSW Resonance

The matter effect of neutrino oscillations is closely related to the density of the medium. If the vacuum mixing angle is small, there exists a lower limit on the amount of matter required to induce significant flavor changes due to the matter effect[36,37]. The amount of matter is characterized by the electron column density along the neutrino trajectory:

$$d = \int_0^l N_e(\chi) d\chi \quad (6)$$

When atmospheric neutrinos enter the Earth's interior from the atmosphere—which is an approximate vacuum—the mixing angle changes due to matter effects, i.e., from θ to θ_m . Since the mixing angle in a vacuum differs from the effective mixing angle in matter (i.e., $\theta \neq \theta_m$), upon entering the Earth, ν_{1m} and ν_{2m} undergo a transition. When $\theta_m = \pi/4$, maximum mixing is achieved (i.e., resonance is formed, at which point $\nu_{1m} = \nu_{2m}$) (Figure 1). This process requires a certain amount of time or a certain width of matter. Since

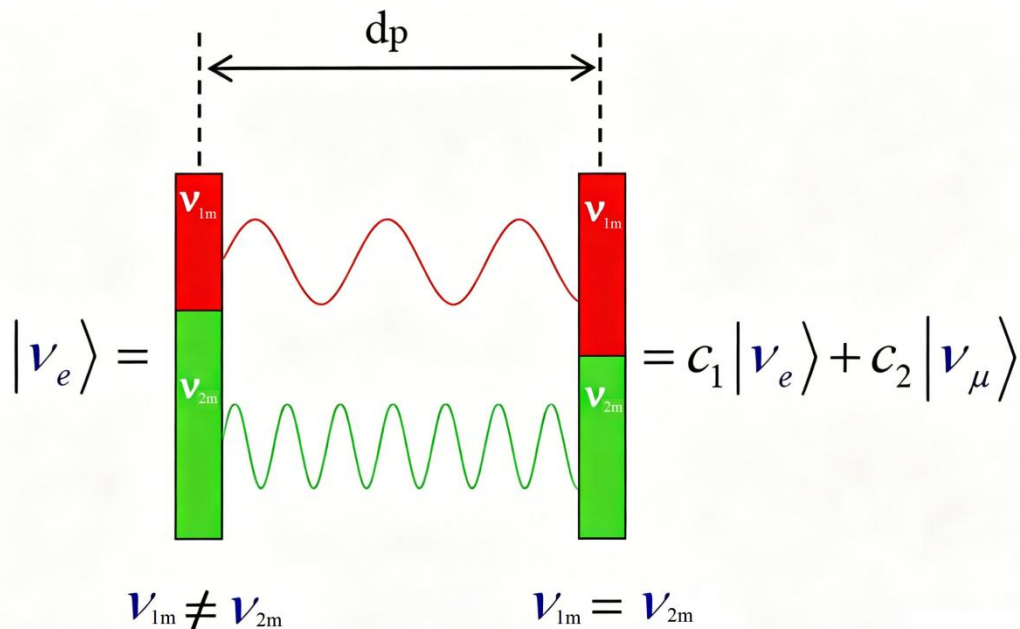


Figure 1 The starting width dp formed by the MSW resonance of neutrino oscillation. neutrinos travel at a speed close to the speed of light, even if the conversion of the neutrino mixing angle can be completed in 10^{-5} seconds, seconds, the width of the region traversed by the neutrinos can reach the kilometer scale.

Zhang and Zhang [31] define the width required for the mixing angle to transition from θ to θ_m and form a resonance as the initiation width of the MSW mechanism, denoted as d_p (Figure 1). Thus, two necessary conditions for the formation of MSW resonance are obtained: 1) the neutrino energy and matter density must satisfy the resonance requirements; 2) the thickness of the matter layer must be greater than d_p . Once the resonance is triggered, it can perturb radioactive nucleon decay; therefore, d_p is also the minimum width for the resonance to perturb radioactive nucleon decay.

2.3 MSW Resonance-Induced Radioactive Decay and Magma Formation

As is well known, resonance represents a type of forced vibration excited by external energy, which can exert highly destructive impacts on fragile systems. After investigating the MSW mechanism, Zhang and Zhang [29,38] further argued that the MSW mechanism essentially corresponds to physical resonance between neutrinos and the surrounding medium. While this resonance strongly modulates neutrino oscillation behavior and boosts the probability of neutrino flavor conversion, it also imposes substantial influences on unstable radionuclides within the medium: it can excite radionuclides to higher energy states and accelerate their decay rates (Figure 2) [29,38]. Since radioactive decay relies on quantum tunneling effects[39] and quantum transition processes [40], decay rates are extremely sensitive to energy fluctuations; even tiny energy perturbations can trigger exponential variations in decay rates.

Atmospheric neutrinos, originating from meson decays produced by cosmic ray interactions with atmospheric nuclei, continuously traverse the Earth's interior[41,42]. Earth's bulk density varies from 1 g/cm³ in oceanic layers up to 13 g/cm³ at the core [43]. The energies of atmospheric neutrinos span the range of 0.1–10⁴ GeV [41,42,44]. Based on the criteria for MSW resonance, atmospheric neutrino energies overlap with Earth's matter density across an extensive interval, allowing MSW resonance to occur between neutrinos and matter in all geospheric layers. During resonance, the energy of atmospheric neutrinos can be expressed as [29,45]:

$$E_{\text{res}} = \frac{\Delta m_{31}^2 \cos 2\theta}{2\sqrt{2}G_F N_e} \approx \frac{\Delta m_{31}^2 [\text{eV}^2] \cos 2\theta_{13}}{7.6 \times 10^{-14} \rho [\text{g/cm}^3]} \text{eV} \quad (7)$$

In the above equation, the relationship between N_e and the density of matter ρ is given by $N_e = Y_e \rho / m_N$, where Y_e is the electron number per nucleon (i.e., the number of electrons per nucleon), and m_N is the mass number of the nucleon. The values of other relevant parameters are: $\Delta m_{31}^2 = 2.49 \times 10^{-14} \text{eV}^2$, $\sin^2 2\theta_{13} = 0.0875$.

The energy of neutrinos producing MSW resonance in the upper mantle is:

$$E_{\text{res}}^{\text{water}} \approx 4.41 \text{ GeV} \left(\frac{3.5 \text{ g/cm}^3}{\rho} \right) \left(\frac{\Delta m_{31}^2}{2.4 \times 10^{-3} \text{ eV}^2} \right) \cos 2\theta_{13} \quad (8)$$

The average densities of the continental crust and core are 2.7 g/cm³ and 10.7 g/cm³, respectively. Using Equation (8), we can similarly calculate that the energies of atmospheric neutrinos producing MSW resonance in the continental crust and core are approximately 11.67 GeV and 2.94 GeV, respectively. The Earth's interior contains abundant radioactive materials. When atmospheric neutrinos form MSW resonance with Earth's matter, they may excite these radioactive materials, increasing their decay probability and releasing more heat.

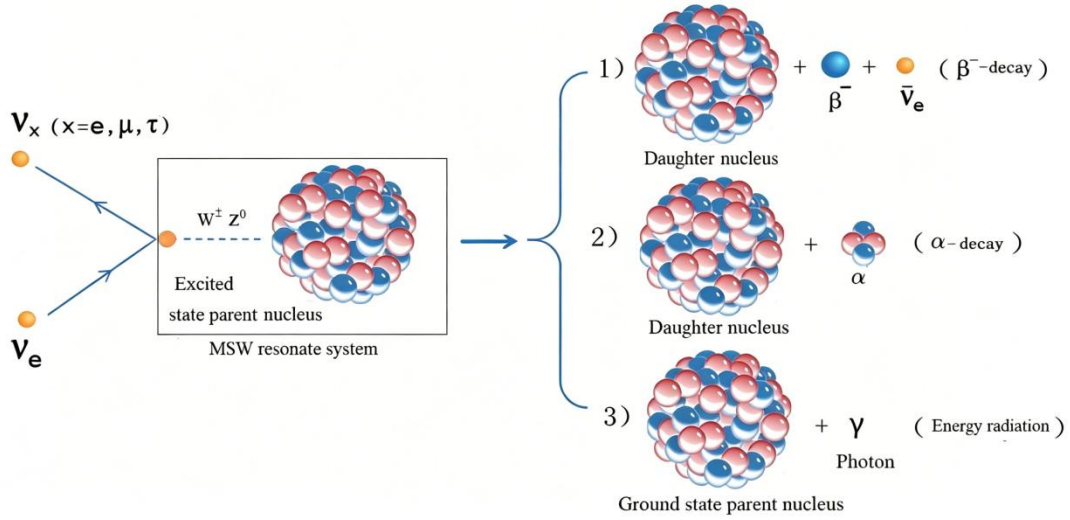


Figure 2 Neutrino oscillations perturb radioactive nuclei to decay in an excited state [46].

Calculations by Zhang and Zhang [29] indicate that in the upper mantle, the decay of just 3.02% of the major radioactive isotopes—such as uranium, thorium, and potassium—is sufficient to trigger melting of upper mantle material. However, in the lower mantle and the core, due to the scarcity of radioactive materials[47], heat released by radioactive decay driven by MSW resonance is inadequate to induce melting. The crust, owing to its complex composition and variable density, contains virtually no rock layers thicker than d_p with uniform density; therefore, MSW resonance can hardly develop, and no melt forms. In contrast, mantle rocks are relatively homogeneous and exhibit moderate plasticity, accompanied by slow, gradual bulk density variations. Within relatively thin layers thicker than d_p , density stays nearly constant; therefore, MSW resonance can be established in the mantle and produce melt[31]. Consequently, Zhang and Zhang [29,30] propose that melt predominantly originates in the upper mantle: atmospheric neutrinos stimulate radioactive decay within this domain, releasing heat and triggering partial melting of surrounding rock. This conclusion not only matches geophysical

observations well [31,48] but also provides a viable magma generation mechanism accounting for a suite of tectonic features, including the asthenosphere, the lithosphere–asthenosphere boundary (LAB), paired metamorphic belts, and nascent oceanic crust [29-31,49].

3. Results and Discussion

Our results indicate that for atmospheric neutrinos to trigger MSW resonance within the Earth's interior, rock layers must maintain uniform density and a thickness greater than 1500 m. Since the crust features complicated, variable density distributions, it fails to satisfy the preconditions for MSW resonance; therefore, MSW resonance cannot take place, nor can magma form. However, previous studies have documented intense magmatic activity within the crust along the northern margin of the SCS [10,14,19,20]. How, then, is such crustal magma generated? After comprehensive analysis, we conclude that magmas within the crust of the northern continental margin of the SCS still originate from radiogenic heating driven by MSW resonance perturbations, and that this magmatism is correlated with changes in seawater depth.

3.1 MSW Resonance in Seawater and OCT Magma Formation

Surface water is a homogeneous medium with a essentially constant density, making it highly susceptible to MSW resonance with atmospheric neutrinos. If the depth of seawater, d_w , is greater than the MSW resonance trigger width, d_p —that is, $d_w \geq d_p$ —then MSW resonance can occur in seawater. The neutrino energy involved in MSW resonance in seawater is:

$$E_{\text{res}}^{\text{water}} \approx 31.5 \text{ GeV} \left(\frac{1 \text{ g/cm}^3}{\rho} \right) \left(\frac{\Delta m_{31}^2}{2.4 \times 10^{-3} \text{ eV}^2} \right) \cos 2\theta_{13} \quad (9)$$

After MSW resonance is established, as neutrinos exit seawater and penetrate the denser continental crust, the adiabatic condition breaks down, and MSW resonance terminates. However, just as MSW resonance has an initiation process, it also features a termination process. In other words, MSW resonance generated within seawater retains its resonant properties due to inertial effects and propagates a finite distance after entering the crust; this distance matches or approximates the MSW resonance initiation width d_p .

Accordingly, seawater-borne MSW resonance extends into the crust and perturbs radionuclides across a certain crustal width, accelerating their decay. Once enough radiogenic heat accumulates, crustal melting occurs and magmatism develops.

Existing studies indicate that magmatism in the northern SCS occurs at water depths of 1500 m to 3000 m or greater (Figure 3) [14,15]. If magmas in this region originate from radiogenic heat released by radioactive decay modulated via atmospheric neutrino oscillation perturbations, water depths between 1500 m and 3000 m exert a controlling influence. A water depth of 1500 m likely

marks the threshold for resonance onset, whereas 3000 m corresponds to the interval where MSW resonance reaches maximum intensity. On this basis, we infer that the minimum initiation width d_p required for MSW resonance and its perturbation of radionuclide decay is approximately 1500 m. When the uniform-density layer thickness exceeds 3000 m, more intense MSW resonance develops and yields substantial radiogenic heat output.

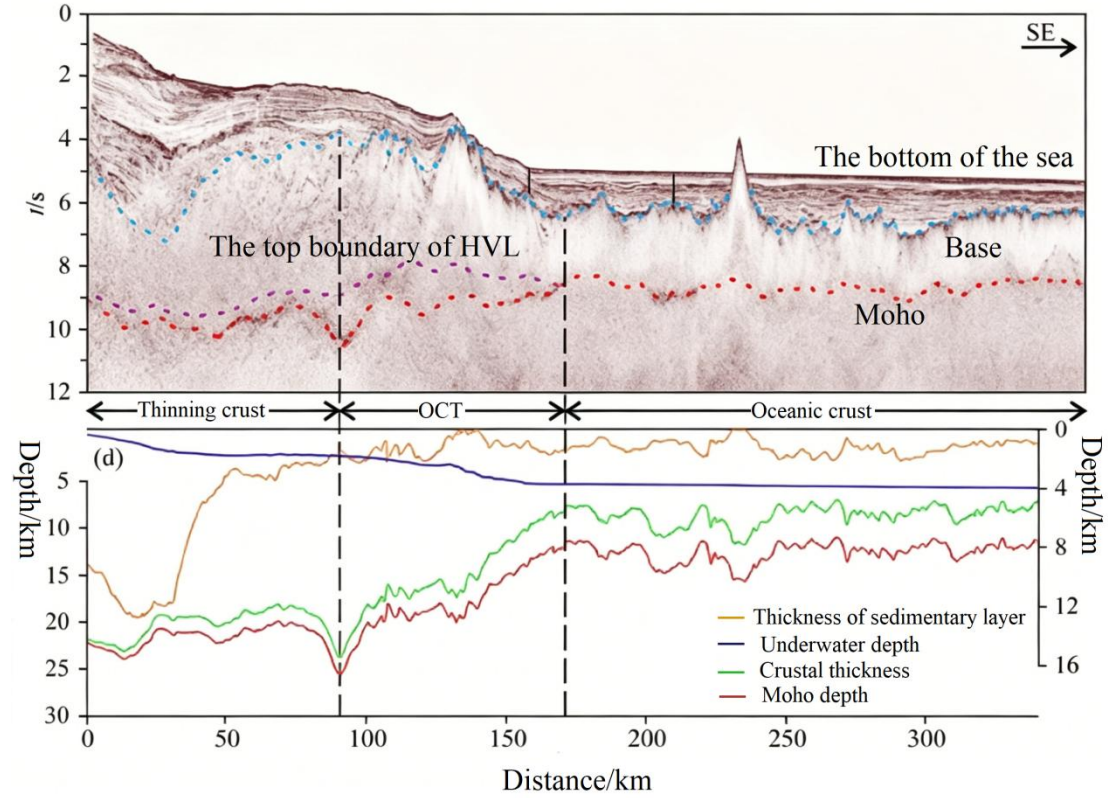


Figure 3 Seismic profile with interpretation of key horizons[50].

3.2 Mechanisms of Crustal Thinning and OCT Formation

OCT feature a gradual shift in crustal attributes from continental to oceanic endmembers. Crustal thickness continuously reduces across this transitional domain, ultimately paving the way for seafloor spreading. The geodynamic drivers of such crustal attenuation have remained controversial for decades[51]. Herein, we elaborate on the mechanisms controlling crustal thinning and OCT development as constrained by seawater depth fluctuations.

(i) When the water depth slightly exceeds 1500 m, atmospheric neutrinos trigger MSW resonance within seawater. Owing to inertial effects, this resonance propagates downward into the underlying crust (including sedimentary sequences) and perturbs local radioactive elements, accelerating their decay rates. This newly established resonance remains relatively weak, and the crust lacks effective heat retention; as a result, radiogenic heat from accelerated decay cannot reach the melting threshold. Instead, the heat only

elevates crustal temperature and drives crustal alteration or metamorphism. Such processes gradually infill crustal pores, lower porosity [52,53], and homogenize bulk density. After sustained MSW resonance perturbation and radiogenic heat accumulation, specific strata develop nearly uniform density and satisfy the preconditions for MSW resonance. Atmospheric neutrinos thus establish secondary MSW resonance within these homogenized layers. Driven by inertial effects, the resonance further disturbs radioactive materials in deeper crust, generating additional decay heat and triggering successive alteration. This feedback loop continuously homogenizes crustal density and sustains new MSW resonance events. After repeated long-term perturbations, three cumulative crustal modifications emerge: 1) Crustal temperature rises progressively. 2) Persistent heating and alteration increase crustal density and improve density uniformity. 3) The lowermost crust lies adjacent to the mantle and holds naturally elevated baseline temperatures. As overall crustal warming proceeds, the basal lower crust crosses the rock solidus, triggering partial melting. Melt migration leaves residual serpentized peridotite, forming a high-velocity layer (HVL) at the crust–mantle boundary (Figure 4). Continued crustal warming drives dehydration of serpentized peridotite, converting it into fresh peridotite. The crustal base acquires mantle-like properties, which ultimately facilitates crustal thinning.

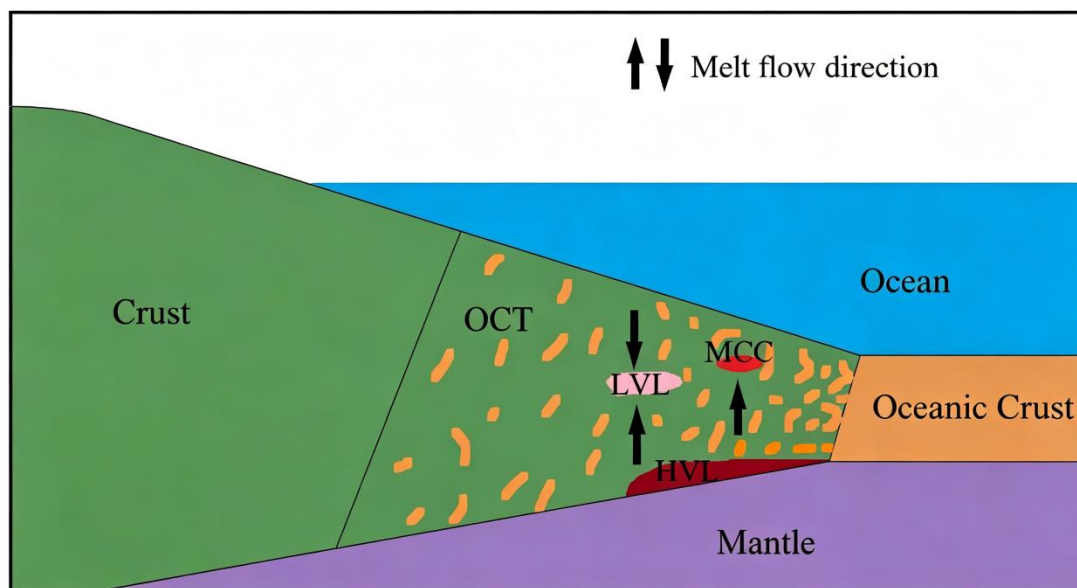


Figure 4 Schematic diagram of the formation of the oceanic-continental transition (OCT).

As seawater depth increases, the width of the resonance zone expands and the resonance effect becomes more pronounced[29,54]. The resonance imposes stronger perturbation on radionuclides and yields greater radiogenic heat; accordingly, the rates of lower crustal melting and crustal attenuation rise. Continuous alteration and partial melting compact the crust and drive subsidence, gradually deepening seawater. Greater bathymetric depth further

amplifies MSW resonance and accelerates melting and thinning of the underlying crust. Thus, crustal thickness exhibits a general negative correlation with water depth: the deeper the water, the thinner the crust.

(ii) As bathymetric depth rises toward 3000 m, radiogenic heat flux driven by MSW resonance perturbations increases substantially. Continuous crustal compaction and bulk heating improve thermal insulation within crustal sequences; radionuclide-rich domains produce sufficient heat to trigger partial melting. This widespread magmatism drives the gradual transformation of continental crust into OCT architecture. Partial melts generated in the upper crust sink gravitationally, given that melt density exceeds that of upper crustal host rocks [55,56]. These melts converge within the middle crust, where rock and melt densities are comparable, creating a distinct LVL(Figure 4). Melting within the middle crust yields melts with nearly identical density to surrounding strata. Such melts either form an in-situ LVL or induce contact metamorphism of adjacent rock masses. Lower-crustal magmas are less dense than host lithologies, so buoyancy drives upward migration into the middle crust. Ascending magmas either build dome-shaped MCC structures (Figure 4) [28] or stagnate to form an LVL. Residual ultramafic minerals persist in the lower crust and constitute the HVL.

(iii) At bathymetric depths greater than 3000 m, MSW resonance peaks and delivers maximal perturbation to crustal radionuclides. Under such intense resonant forcing, partial melting occurs even in the uppermost radionuclide-rich crustal layers. Melt produced in the upper crust sinks gravitationally[55,56], leaving residual peridotite in shallow domains; some melts also crystallize in situ to form peridotite [57]. Subsequent hydrothermal alteration of these peridotites produces serpentinized peridotite (Figure 4)[58-61]. Melt percolating downward progressively cools and crystallizes into gabbro. This creates a two-tier crustal succession with serpentinized peridotite overlying gabbro, marking the complete transition to oceanic crust.

(iv) During the transition from OCT to oceanic crust, crustal thinning takes place as continuous temperature elevation triggers partial melting at the crustal base. Driven by buoyancy, melt migrates upward through the hot lower oceanic crust. Ascending melt dissolves and extracts pre-solidified low-melting fractions and may even partially remelt gabbro to generate plagioclase granite [62]. When melt ascends into the cooler upper oceanic crust, the highly brittle nature of upper crustal rock prevents pervasive percolation, so the melt becomes trapped beneath this brittle lid. Combined stress from hot underlying magma and overlying cold seawater fractures the lid, generating abundant vertical fractures. Magma erupts upward through these fracture channels and rapidly rises to the base of cold sedimentary sequences, where it solidifies into pillow basalt. Magma also infills the fractures to form sheeted dikes (Figure 5),

collectively producing oceanic crust matching the architecture of the Penrose model[30,63].

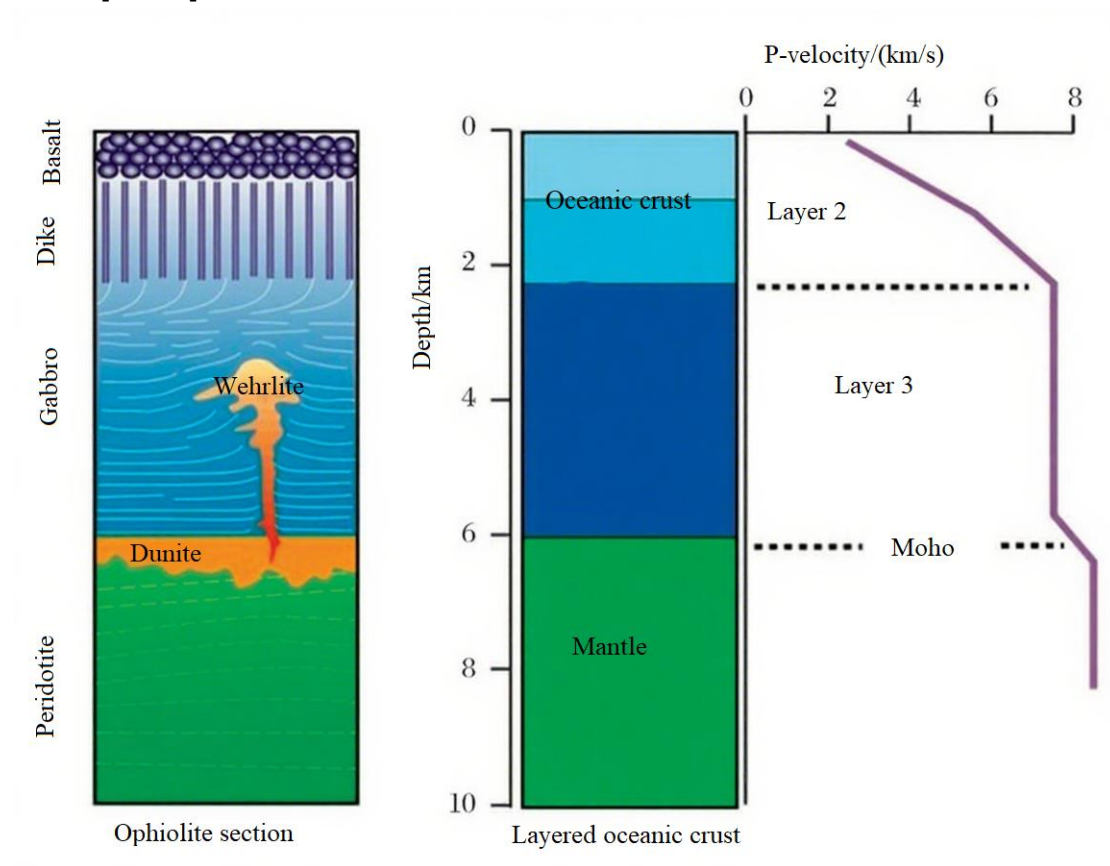


Figure 5 Penrose model of oceanic crust based on Oman ophiolite and its comparison to seismic data[63].

Finally, it should be noted that during the transformation of continental crust into OCT and subsequently oceanic crust, aside from seawater depth, the initial crustal radioactive content acts as another critical controlling factor. Where crustal sequences are enriched in radionuclides, radiogenic heat output rises, crustal warming accelerates, and magma generation is enhanced. This speeds up the crustal transition toward OCT and oceanic crust. In contrast, crust depleted of radioactive species undergoes slower transition to OCT and oceanic crust. If radionuclide concentrations are extremely low, the crust may permanently retain continental signatures and never evolve into oceanic crust. This accounts for the preservation of relict continental crustal fragments within certain oceanic terranes[50,64].

3.3 An Explanation for Magmatic Diversity in the OCT

Geochemical characterization of seamount volcanics along the northern South China Sea margin identifies EMI-enriched mantle basalts, intermediate–acid volcanic rocks, and depleted Nb/U ratios, recording continental crustal assimilation during magma genesis and evolution; sedimentary contaminants derived from deep marine sequences are also detected in these rock suites [22,25]. The continental crustal geochemical signal is conventionally

interpreted as crustal contamination during upward melt migration. By contrast, sedimentary components are hypothesized to be recycled via subduction processes in prior work [22,25]. Both frameworks remain unvalidated conjectures with critical geophysical inconsistencies. Sediments are low-density, weakly consolidated deposits, rendering synchronous subduction with dense oceanic crust into the high-density mantle physically unreasonable. Our foregoing analysis demonstrates OCT magmas form hybrid mixtures of mantle-derived exogenous melts and crustal endogenous melts (including sedimentary fractions), where mixing ratios are controlled by the magnitude of radiogenic heat production. This variable hybridization generates continuous compositional trends spanning acidic to basic rock types. At shallow water depths, weak radiogenic heating only drives crustal alteration and metamorphism, producing small volumes of crust-dominated melt with minimal mantle contribution, corresponding to intermediate–acid rock suites [24,25,65]. Increasing bathymetry amplifies crustal thermal input and concomitant mantle warming [66]. Basic and ultrabasic mantle melts are produced in greater volumes, ascending through crustal strata and triggering episodic volcanism. Progressive mantle melt addition drives a compositional transition of hybrid magmas from intermediate–acid to intermediate–basic.

As the crust compacts and oceanic crust (ocean basins) forms, the crust subsides and water depth increases. At this evolutionary stage, atmospheric neutrino oscillations exert amplified perturbations on radionuclides within the underlying OCT and oceanic crust. This elevates radiogenic heat output and melt generation, giving rise to intensified magmatism[23,67]. Several scholars attribute the intense magmatic pulse after SCS opening to mantle plume activity. Nevertheless, typical mantle plume signatures include localized oceanic crust thickening. If a mantle plume had existed along the northern SCS margin, anomalous crustal thickening should be detectable here; yet no such feature has been identified by geophysical surveys[68]. On the contrary, the Pearl River Mouth Basin recorded accelerating subsidence throughout the magmatic peak[69,70], and none of these geological observations support the mantle plume hypothesis[71].

3.4 Evidence of Oceanic Crustal Melting

Seawater-hosted MSW resonance is capable of perturbing radionuclide decay within underlying crustal strata. Given that most ocean basins feature bathymetry greater than 1500 m, a natural question arises: can MSW resonance affect the entirety of oceanic crust and generate partial melts? We affirm this possibility, especially within the homogeneous lower oceanic crust. Direct observation of such melts remains difficult, however, owing to their extremely low volumetric abundance. Multiple lines of geological evidence support partial melting of oceanic crust, as outlined below:

(i) Plagioclase granites represent a ubiquitous acidic lithology in oceanic crust, and constraining their origin is essential to reconstruct oceanic crustal

evolution. Two classic genetic models have been widely adopted: 1) late-stage fractional crystallization of mantle-derived basalt under low pressure[72-74]; 2) crustal anatexis driven by hydrothermal modification of mafic crust, facilitated by deep magma infiltration[75-78]. Neither of these two frameworks can fully reconcile natural geological observations. For one thing, fractional crystallization conflicts with field constraints. Late-stage plagioclase granite melt possesses the lowest density and should therefore occur alongside late-formed pillow basalt. Geologic surveys instead document plagioclase granite interlayers within gabbroic sequences [79], with coherent geochemical signatures matching gabbro [80].

For another, laboratory melting experiments confirm plagioclase granite generation via partial melting of oceanic crust [76,81,82]. Even so, hydrothermal alteration cannot reach the required melting temperature. Typical oceanic hydrothermal fluids peak at 500 °C, yet the hydrous solidus of mafic crust is no lower than 850 °C [76]. This thermal discrepancy indicates that only radiogenic heating amplified by neutrino oscillation-induced MSW resonance can provide sufficient heat to drive partial melting of oceanic crust.

(ii) Seafloor-exposed abyssal peridotites fall into two genetic categories:

melt-extraction residues and cumulates formed by magmatic crystallization [57]. Peridotites of both origins commonly coexist along oceanic spreading systems. Traditional models argue that slow and ultra-slow spreading ridges suffer inadequate magma flux, enabling direct tectonic exhumation of asthenospheric peridotite following crustal separation; these peridotites are therefore regarded as primitive upper-mantle material. This hypothesis predicts a full mantle lithology succession beneath peridotite outcrops, a prediction contradicted by geophysical observations[83]. Geophysical surveys confirm thick oceanic crust underlies most peridotite-bearing slow/ultra-slow ridges, with mean crustal thickness nearly identical to that of fast-spreading systems. This constrains peridotite to shallow surface layers, while gabbro dominates deeper crustal intervals. The surficial distribution of peridotite points to an origin via in-situ crustal melting and subsequent melt removal. No established physicochemical trigger can account for seafloor crustal melting except the MSW resonance-enhanced radionuclide decay mechanism presented in this paper.

(iii) Ocean drilling programs have identified extensive porous melt percolation

networks hosted within gabbroic oceanic crust[84-86]. Drilling data from Atlantis Bank on the Southwest Indian Ridge[84] disprove a genetic link between lower crustal stratigraphy and crystallization within large steady-state magma chambers. Mineral fabrics throughout the lower crust instead record dynamic crystallization, consistent with construction via repeated, episodic melt intrusions. Extensive pervasive percolation and melt-rock interaction within oxidized gabbroic layers govern the stratigraphic architecture and

geochemical evolution of the lower oceanic crust. Whole-rock geochemistry records protracted, multi-stage crustal evolution; classic single-stage models (fractional crystallization, static in-situ crystallization) cannot account for the wide geochemical variation observed in gabbroic rock suites. These crustal evolutionary features align closely with a heating mechanism rooted in MSW resonance-accelerated radionuclide decay. Neutrino oscillation is a probabilistic physical process, rendering radiogenic heat flux and melt production stochastic and episodic. Melt transport and intrusion therefore occur in small, discrete pulses. Furthermore, MSW resonance generates melts pervasively throughout the mantle and lower crust, so lower crustal melt networks represent a hybrid mixture of in-situ crustal melts and upward migrating mantle melts. Long-term cumulative processes including melt extraction, infiltration, and reactive flow imprint unique geochemical fingerprints on the lower oceanic crust—features that cannot be fully reproduced by conventional simplistic petrogenetic models.

4. Conclusion and Issues

This work presents a new mechanism for magma generation and OCT formation within the crust of passive continental margins. According to this mechanism, MSW resonance generated by atmospheric neutrinos in seawater can, through inertial effects, perturb the radioactive decay of underlying crustal materials, generating heat and magma, which in turn lead to crustal thinning and OCT formation. Consequently, magmatism acts as the direct driving force behind crustal thinning and OCT formation along the northern margin of the SCS, with no additional geodynamic mechanisms required.

At present, the mechanism proposed in this paper is preliminary and contains several uncertainties. In particular, the fundamental premise upon which this mechanism relies—that MSW resonance perturbs radioactive materials to accelerate their decay—has not yet been experimentally verified. In this paper, we calculate that the trigger width for MSW resonance formed by neutrino oscillations is 1500 m. This width also represents the threshold above which MSW resonance can perturb radioactive decay; therefore, it can serve as a criterion to test the validity of the viewpoints presented in this paper and judge whether MSW resonance can indeed alter the decay rate of radioactive materials. Accordingly, future research will focus on experimentally verifying whether radioactive materials at seawater depths greater than 1500 m experience accelerated decay induced by MSW resonance.

Data availability

Available on request All the data are real and original already mentioned in the paper.

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