

# Neutrino Oscillation, Radioactive Decay, Magmatic Activity and Earthquake Formation

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## Abstract

The mechanism underlying earthquake formation has long been a topic of scholarly debate. Leveraging the latest research findings on neutrino oscillation-induced radioactive decay and magma genesis, this study proposes a dynamic model for earthquake generation by analyzing both the stress field arising from magma intrusion into the crust and the mechanical strength characteristics of rocks. Recent research has established that magma originates from the thermal energy released by radioactive decay in the upper mantle and asthenosphere—a process triggered by atmospheric neutrino oscillations—which induces partial melting of the materials in these geological layers. Building on this, our research posits that once magma forms, it is driven upward into the crust by a combination of buoyancy forces and tectonic stresses. It then migrates toward low-stress zones, such as the interiors of mountain ranges (*i.e.*, arch structures) or fault zones, where it generates high-temperature environments and modifies the local stress field. This, in turn, exerts thermo-compressive stress on the surrounding rock mass, leading to the gradual accumulation of stress. When the accumulated elastic stress surpasses the rock's failure threshold, an earthquake is initiated. Additionally, within the plastic mantle, heat generated by radioactive decay can induce phase transitions and the production of substantial volumes of gas. These processes cause material expansion or even gas-driven explosions, which further trigger rock fracturing and subsequent seismic activity. Finally, based on this seismic mechanism, we explain the formation of earthquake precursors such as cosmic ray, ionospheric, and radon anomalies.

## Keywords

Geodynamics, Neutrino Oscillation-Induced Radioactive Decay, Magmatic Activity, Earthquake Mechanism, Earthquake Precursor

## 1. Introduction

Numerous studies and hypotheses have been proposed concerning the causes of earthquakes [1]-[5]; however, no unified theory has been established to date. This is primarily because none of these hypotheses can fully explain key fundamental seismic facts and phenomena. For example, the widely recognized elastic rebound hypothesis is not only confronted with the “heat flow paradox” but also unable to account for intermediate- and deep-focus earthquakes [1] [5]. Despite ongoing intense debate regarding the origins of earthquakes, several points of consensus have emerged in the scientific understanding of seismic events. These include: 1) Earthquakes involve the massive release of energy, which is preceded by an energy accumulation process. Thus, to understand the mechanisms of earthquake formation, it is essential to identify the source of this accumulated energy [1]; 2) Anomalies—including geomagnetic, ionospheric, geothermal, and geochemical anomalies—occur both before and after earthquakes [6]-[8]; 3) Earthquakes exhibit distinct distribution patterns. Vertically, most are shallow-focus events with a focal depth of no more than 70 km; the number of earthquakes decreases exponentially as depth increases, reaching a minimum at approximately 300 km. Subsequently, seismic activity increases again, peaking at around 600 km before abruptly ceasing at the base of the mantle transition zone (MTZ). To date, no earthquakes have been detected in the lower mantle [4]. Horizontally, earthquakes are predominantly concentrated in specific zones. For instance, the Circum-Pacific Seismic Belt accounts for ~80% of global shallow-focus earthquakes, 90% of intermediate-focus earthquakes, and nearly all deep-focus earthquakes. The remaining ~10% of earthquakes are mainly distributed along the Mediterranean-Himalayan-Indonesian Seismic Belt and the mid-ocean ridge seismic belts [1] [9]. These points of consensus regarding earthquakes also act as constraints for theories of earthquake formation. Any valid theory of earthquake formation must satisfy the aforementioned conditions.

Energy is the most critical factor in earthquake formation. Previous studies [6] [10] [11] have suggested that magmatic activity fosters and triggers earthquakes, implying that magma provides the energy required for earthquake genesis. However, these studies did not elaborate on the formation mechanism of magma itself—thereby leaving the ultimate source of this energy unclear.

Recently, Zhang and Zhang [12] proposed a novel theory for magma formation. They argue that atmospheric neutrino oscillations induce radioactive decay, which generates heat to partially melt rock materials in the upper mantle and asthenosphere; this process is posited as the primary driver of magma formation. Building on this magma formation theory, Zhang and Zhang [12]-[14] successfully explained the formation of a series of geological structures both inside and on the Earth’s surface, including the asthenosphere, lithosphere-asthenosphere boundary (LAB), new oceanic crust at mid-ocean ridges, marine magnetic anomalies, oceanic core complexes (OCCs), and paired metamorphic belts. This work clearly establishes magma as the primary energy source driving Earth’s evolutionary processes.

To address the aforementioned knowledge gaps, this paper analyzes the thermal pressure effects of magma on surrounding rocks, drawing on both the neutrino oscillation-induced radioactive decay mechanism [15] and the aforementioned novel magma formation theory [12]. On this basis, we propose a magma-driven earthquake formation mechanism that effectively accounts for the various constraints governing earthquake genesis.

## 2. Energy Sources of Earthquakes

Regarding the new theory of neutrino oscillation-induced radioactive decay and magma formation, Zhang and Zhang [12] [15] have provided a detailed discussion. For further details, please refer to Zhang and Zhang's reference [12] [15]. Below, we offer a brief introduction to the relevant content.

### 2.1. Neutrino Oscillation-Induced Radioactive Decay

Wolfenstein [16] and Mikheyev and Smirnov [17] successively investigated the material effects of neutrino oscillations, establishing the evolution equation for neutrinos propagating through matter. By solving this equation, they derived the probability of neutrino flavor conversion. Taking two-flavor neutrinos (e.g.,  $\nu_e \leftrightarrow \nu_\mu$ ) as an example, the flavor conversion probability during propagation through constant-density matter can be expressed as:

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2 2\theta_m \sin^2 \left( \frac{\Delta m_m^2 L}{4E} \right) \quad (1)$$

In the above equation,  $E$  is the energy of neutrinos,  $L$  is the oscillation baseline length,  $\theta_m$  is the mixing angle of matter effects, and  $\Delta m_m^2$  is the square difference of effective mass. The correlation values are given by the following formulas:

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A_{CC}} \quad (2)$$

$$\Delta m_m^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2} \quad (3)$$

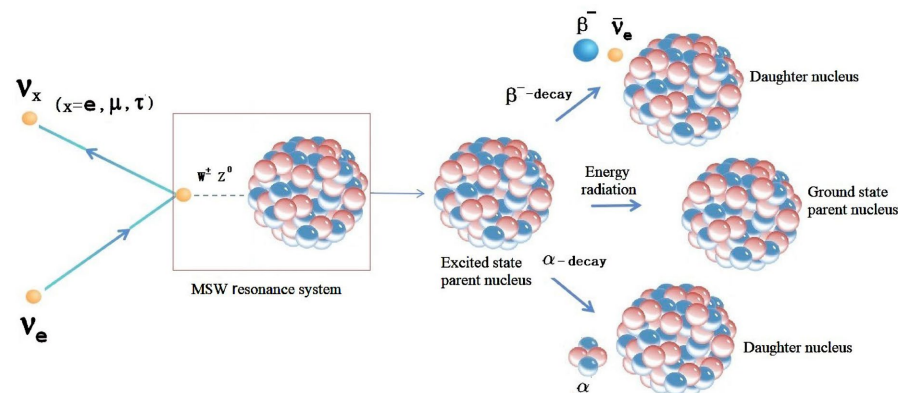
In Equation (2) and Equation (3),  $\theta$  is the mixing angle in vacuum,  $\Delta m^2 = |m_2^2 - m_1^2|$  is the square difference between the masses of two eigenstates, and  $A_{CC} \equiv 2EV_{CC} = 2\sqrt{2}EG_F N_e$  is the potential of the charged material ( $G_F$  is the Fermi constant, and  $N_e$  is the number density of electrons in the material).

When the following conditions are met, neutrinos will resonate with the atoms in the medium:

$$V(N_e) = V_{CC} = \sqrt{2}G_F N_e = \frac{\Delta m^2 \cos 2\theta}{2E} \quad (4)$$

Since this resonance mechanism was jointly discovered by Mikheyev, Smirnov, and Wolfenstein, it is named the Mikheyev-Smirnov-Wolfenstein (MSW) mechanism. During resonance, the neutrino flavor conversion probability reaches its maximum value. Building upon this, Zhang and Zhang [12]-[15] further proposed that the MSW mechanism actually represents a physical resonance between neutri-

nos and medium atoms, involving energy excitation. This resonance significantly influences neutrino oscillation behavior, increasing neutrino flavor conversion probabilities while also affecting medium atoms. It excites unstable radioactive nucleons in the medium into excited states, thereby increasing their decay rates [12] [13] (Figure 1). Since radioactive decay is a tunneling effect [18] and quantum transition phenomenon [19], it is highly energy-sensitive; even negligible energy excitation can cause exponential increase in decay rates.



**Figure 1.** Neutrino oscillations perturb radioactive nuclei to decay in an excited state. This image has been modified according to reference [12].

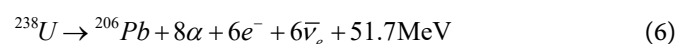
The Earth's interior contains abundant radioactive materials. If neutrinos traversing the Earth can resonate with terrestrial matter via MSW, this resonance would undoubtedly excite the Earth's radioactive substances, increasing their decay probability and decay heat generation. Based on resonance conditions, it is readily apparent that atmospheric neutrinos passing through the Earth can form MSW resonance within its interior (Note: According to the resonance condition, due to the relatively low energy, solar neutrinos cannot form MSW resonance with matter inside the Earth). From Equation (4), the energy of atmospheric neutrinos during resonance is given by [12] [20]:

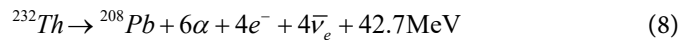
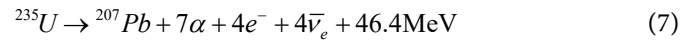
$$E_{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F N_e} \approx \frac{\Delta m_{31}^2 [\text{eV}^2] \cos 2\theta_{13}}{7.6 \times 10^{-14} \rho [\text{g/cm}^3]} \text{eV} \quad (5)$$

where  $N_e$  relates to material density  $\rho$  as  $N_e = Y_e \rho / m_N$ , where  $Y_e$  is the electron molecular number (*i.e.*, electrons per nucleon) and  $m_N$  is the nucleon mass number. When the energy of atmospheric neutrinos ( $E_{res}$ ) and material density ( $\rho$ ) satisfy Equation (5), MSW resonance can occur.

## 2.2. Formation and Migration of Magma

The four primary radioactive isotopes within the Earth— $^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ —undergo the following decay reactions under neutrino oscillation perturbations [21]:





Research indicates that the energy spectrum of atmospheric neutrinos is exceptionally broad, ranging from approximately 0.1 to  $10^4$  GeV and reaching up to the TeV level [20] [22] [23]. Given that the density of Earth's material ranges from 1 to 13 g/cm<sup>3</sup> [24], according to Equation (5), all of Earth's material can form MSW resonance with atmospheric neutrinos. In other words, radioactive materials within Earth's various layers can be stimulated by MSW resonance to accelerate decay and generate heat. However, due to the scarcity of radioactive substances in the lower mantle and core, the heat produced by radioactive decay from atmospheric neutrino oscillations is insufficient to cause material melting. Consequently, it is difficult to form significant molten material or produce a substantial thermal effect. Although the crust is rich in radioactive materials, the MSW resonance between neutrinos and matter requires an initiation process. After entering the crust, neutrinos typically remain in the initiation phase where resonance has not yet formed. Full MSW resonance only occurs upon reaching the upper mantle. Therefore, radioactive materials in the crust are not resonantly excited and do not produce melt. Calculations indicate [12] that if MSW resonance could excite decay in 3.02% of the upper mantle's primary radioactive materials, it would suffice to cause upper mantle melting. Therefore, Zhang and Zhang [12]-[14] propose that Earth's internal melts (or magma) primarily originate from the upper mantle and asthenosphere.

The melting effect of neutrino oscillation perturbations first occurs in minute regions enriched with radioactive substances, forming melt pocket of various shapes [12]. These tiny melt pockets are typically randomly distributed throughout the upper mantle, disconnected from one another, and represent the embryonic stages of magma. As MSW resonant perturbations persist, radioactive heating intensifies, gradually enlarging the melted zones. These melt pockets progressively transform into massive droplets, coalescing with surrounding melt pockets and droplets to form mobile melts or magmas. Driven by buoyancy, these melts or magmas ascend. Upon reaching the lithosphere, magma migration is further influenced by tectonic stresses. The upper mantle exhibits plastic behavior, allowing magma to ascend primarily through permeation [12] [13]. Upon reaching the rigid crust, mineral crystals resist creep, preventing further permeation upward. Magma can only migrate along fractures toward regions of lower stress. Since mountain ranges and their flanking basins form a massive arch-like structure, the enormous gravity of the mountain range's crust can be converted into lateral pressure through the arch structure and transmitted to the basins on both sides, resulting in much higher pressure below the basin than below the mountain range [13] [25]. Consequently, low-stress zones form beneath the mountains, while the

flanking basins become high-stress zones [14]. Consequently, magma originating from the upper mantle and asthenosphere typically does not ascend vertically but rather flows obliquely upward, gradually converging from the flanking basins toward the upper crust of the mountain range [13], ultimately emplacing within the crust of the mountain's core. Thus, orogenic belts (including island arcs and mid-ocean ridges) are typically among the regions with the most intense magmatic activity.

### 3. The Force Source of Earthquakes

Earthquakes result from the long-term accumulation of stress, which is commonly regarded as tectonic stress. Only two primary forces exist within the Earth's interior: gravity and thermal pressure generated by the planet's heat [26]. All other tectonic stresses are derived from these two fundamental forces.

#### 3.1. Gravity

Gravity is the most evident and critically important force in tectonic movements. Both the early gravity isostasy [27] [28] and the contemporary negative buoyancy [29] are founded upon gravitational effects. The classical gravity isostasy describes the balance of local vertical stresses confined solely to the lithosphere above the asthenosphere. At a depth  $h$ , the vertical stress  $\sigma_{zz}$  can be expressed as [30]:

$$\sigma_{zz} = g \int_0^h \rho(z) dz \quad (10)$$

where  $g$  is the gravitational acceleration, and  $\rho(z)$  denotes density as a function of depth ( $z$ ). For constant density, this simplifies to:

$$\sigma_{zz} = \rho gh \quad (11)$$

This represents the pressure on a unit column of lithosphere at depth  $h$  under hydrostatic equilibrium ( $\sigma_{zz} = \sigma_{xx} = \sigma_{yy}$ ), also known as confining pressure.

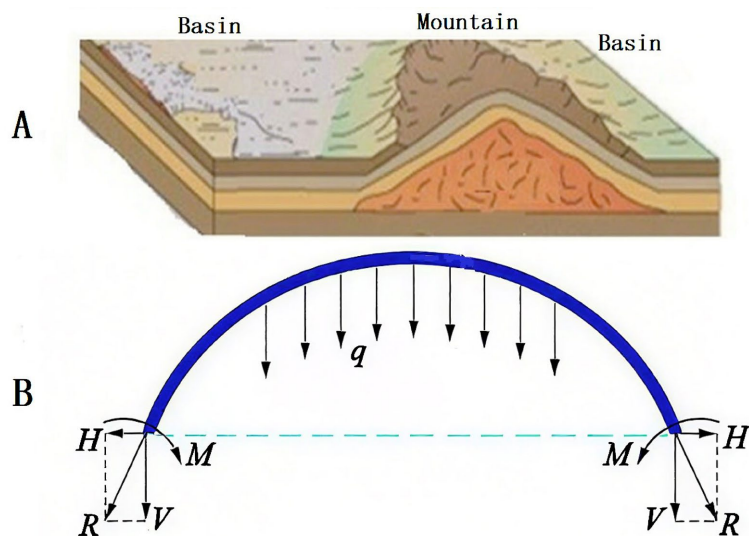
At the equilibrium base of the lithosphere, the gravitational potential of a column per unit area can be expressed as the integral of vertical stress. Therefore, lateral variations in gravitational potential between two adjacent lithospheric plates can induce horizontal forces, providing a significant driving force for horizontal movement and deformation of the lithosphere. In other words, gravity not only exerts vertical forces but also generates horizontal stresses. Thus, a complete gravitational stress formula should include both vertical ( $\sigma_v$ ) and horizontal ( $\sigma_H$ ) components [5]:

$$\sigma_v = \rho gh \quad (12)$$

$$\sigma_H = \frac{\mu}{1-\mu} \sigma_v \quad (13)$$

where  $\mu$  is Poisson's ratio. In actuality, the Earth is a spherical body, and there is no strictly horizontal stress; instead, only circumferential stress exists. Research shows that under the crust's own weight, the curved (or arched) crust exerts mutual compressive forces on each other, generating significant circumferential (or

lateral) stress. This circumferential stress generally exceeds the gravitational force acting on the crust [31]. In other words, the arched structure of the crust converts the majority of its own weight into circumferential (or lateral) stress exerted on the surrounding rock formations. The commonly referenced horizontal principal stress is essentially the circumferential compressive stress derived from the crust's self-weight [31]. In orogenic belts, mountain ranges flanked by basins (or plains) form an even more distinct arched structure. The stress characteristics of an arch structure are as follows: under the vertical load  $q$  acting on the arch, the support point generates a vertical reaction force  $V$  and simultaneously produces a horizontal thrust  $H$  (as shown in **Figure 2**). Due to the presence of this horizontal thrust, the bending moment  $M$  of the arch is significantly smaller than that of a horizontal structure of the same span. Consequently, the entire arch structure primarily bears compressive stress [31]. It can be demonstrated [13] [25] [31] that due to the arch effect, the self-weight of mountain ranges partially transforms into compressive stress on basins (or plains). Consequently, the stress on rocks beneath mountains is substantially less than the static rock pressure calculated based on depth, while overburden pressure exceeding static rock pressure develops beneath basins. This phenomenon also contributes to global gravitational imbalance [28].



**Figure 2.** Basin mountain arch structure and arch structure stress diagram (Image quoted from [25]).

### 3.2. Thermal Stress

As magma ascends into the crust, temperature variations induce volume changes in materials, inevitably generating thermal stress. Within the lithosphere at depths of 15 - 20 km, under conditions of isotropic elasticity and constant pressure, stresses arising from temperature changes ( $\Delta T$ ) satisfy Duhamel-Neumann's law. Applying this to the equilibrium equations for continuous media simplifies the thermo-elastic problem into an elastic one, yielding the thermal stress ( $P_t$ ) as [30]:

$$P_t = \sigma_{xx} = \sigma_{yy} = -\frac{E}{1-\mu} \alpha^L \Delta T \quad (14)$$

where  $E$  is Young's modulus,  $\mu$  is Poisson's ratio, and  $\alpha^L$  is the linear thermal expansion coefficient. Using known crustal parameters, calculations indicate that at  $\Delta T = 100$  K, thermal stresses of approximately 100 MPa can be induced [30]. In reality, temperature changes exceeding 1000 K caused by neutrino oscillation-induced radioactive heating [12] result in immense stress variations.

Of course, beyond gravitational and thermal pressure forces, some propose that Earth's rotation, as well as tidal forces from the Moon and Sun, also exert stresses on the crust. However, these forces are extremely weak, making them unlikely to serve as driving forces for tectonic movements.

### 3.3. Rock Strength Response to External Forces

When external forces act on a rock, they induce deformation and motion in the rock. The magnitude of such a response is closely tied to the rock's mechanical strength [28]. Rock strength can be defined using a range of mechanical parameters, while the macroscopic mechanical properties of rocks are strongly associated with interatomic potential energy, crystal defects, grain size, and grain boundaries.

When a rock is subjected to compressive stress, interatomic distances shorten and bond angles alter—both of which lead to lattice distortion. If the external force is small, the rock's microstructure can revert to its original state once the force is removed; macroscopically, the observed deformation exhibits a linear relationship with the applied pressure. This phenomenon reflects the elastic behavior of the rock.

When the external force exceeds a certain threshold, mechanisms including atomic diffusion, slip plane migration, and recrystallization become active: these processes increase defect density, modify grain size, and restructure the rock's original microstructure. When the external force is subsequently removed, the rock (as a solid) retains permanent macroscopic deformation—a phenomenon termed the rock's plastic deformation. At this stage, the state of the rock when the force is still applied is referred to as its plastic state.

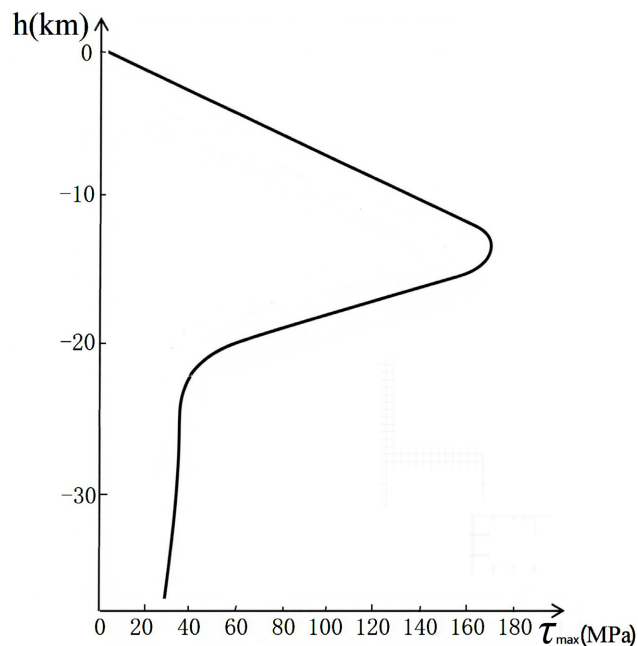
If pressure is reapplied after the initial force is removed, the rock will still exhibit elastic behavior under low stress levels. However, its elastic modulus and elastic limit will differ from their prior values, as the microstructure has been permanently altered. Factors like increased temperature can promote the transition between elastic and plastic behavior in rocks. Thus, elasticity and plasticity are two distinct states that the same rock can exhibit under different pressure conditions [5].

When subjected to external compression, a rock first develops elastic stresses. As the external pressure intensifies, the rock then undergoes plastic deformation, and this plastic deformation acts to dissipate the applied compressive stress. Research shows that if a unidirectional force is applied to a rock over an extended period (even a small force) while the rock remains within its yield strength range, creep can be induced. This creep is essentially driven by plastic deformation. Consequently, many

scholars argue that crustal rocks also exhibit rheological properties [5].

However, if the applied external stress becomes excessively high, plastic deformation and creep will be unable to reduce the elastic stress sufficiently or in a timely manner, resulting in stress accumulation. Once the accumulated stress exceeds the rock's failure strength, the rock will fracture.

In practice, the yield strength of different rock types varies with increasing confining pressure and temperature. Generally, the strength of shallow crustal rocks increases with rising confining pressure yet decreases with increasing temperature. In the deep crust, as rocks undergo a brittle-to-ductile transition, their strength decreases markedly and stabilizes at specific depths [5] [10]. **Figure 3** illustrates how the shear strength of rocks varies with depth. Similar trends are observed for other mechanical properties of rocks. Typically, higher mechanical strength in rocks is associated with greater stress accumulation capacity [32], higher energy storage potential, and a larger external force required to induce failure. Consequently, rock fracturing releases a greater amount of energy.



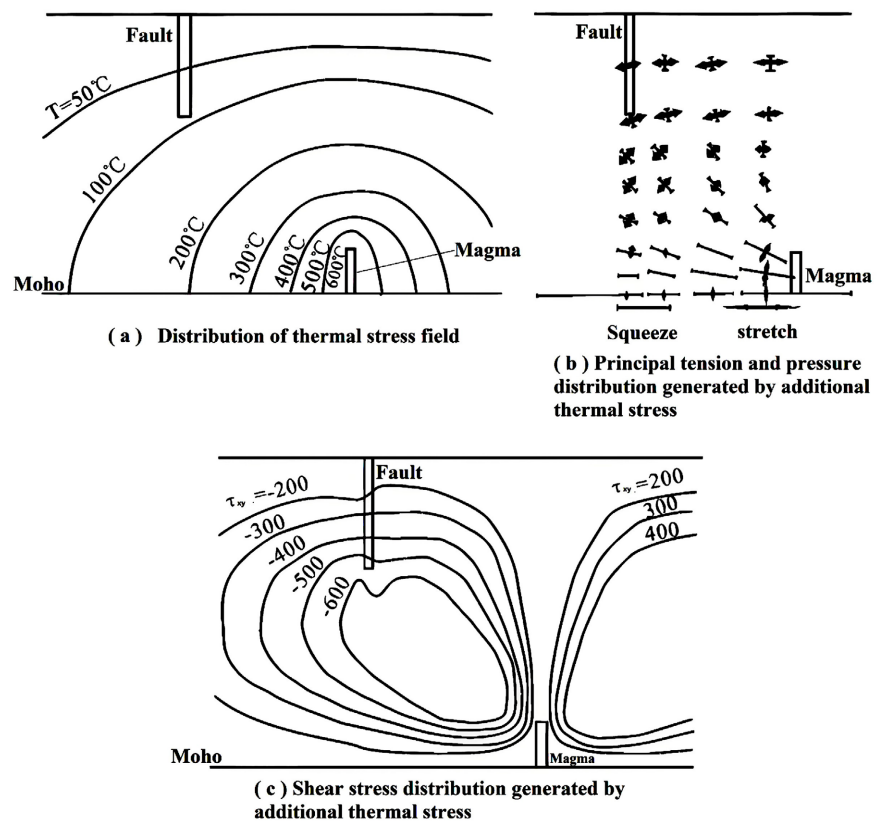
**Figure 3.** The variation of maximum shear strength of crustal rocks ( $\tau_{\max}$ ) with depth ( $h$ ). This figure has been modified based on references [5] and [10].

## 4. Dynamic Mechanisms of Earthquake Formation

### 4.1. Formation of Shallow Earthquakes

1) Nurturing of Shallow Earthquakes. Earthquakes are both a product of stress accumulation and not merely simple stress accumulation. First, because the Earth is an approximate sphere, an arching effect exists, whereby the crust's self-weight is typically partially converted into circumferential stress applied to the rock on both sides [25] [31]. Circumferential stress exerts a compressive force on rock.

Meanwhile, thermal stress radiating from the Earth's interior typically propagates in all directions, imposing intense shear stress on the arched (or curved) crust. Under identical conditions, the compressive strength of rock is usually far greater than its shear strength. For example, granite has a compressive strength of 100 - 250 MPa, while its shear strength is only 20 - 50 MPa. Thus, thermal stress plays a decisive role in the formation and triggering of earthquakes. Secondly, due to the arching structural effect, magma typically converges from the margins toward the interior of mountain ranges. This creates zones with differing temperature-pressure environments within orogenic belts [14]. These disparities in temperature and pressure give rise to two key effects: a) Alterations in the mechanical strength of rocks. In the mountain interior, where magma convergence drives up temperatures, rocks exhibit diminished brittleness and enhanced ductility—ultimately resulting in reduced overall mechanical strength. By contrast, at the mountain margins (the transitional zones between mountains and basins), lower magma accumulation leads to rocks that are more brittle and possess higher mechanical strength. b) Generation of a thermal stress field. At the mountain's core, with the magma convergence zone as its center, a thermal field extends outward, featuring a gradual temperature decrease [10] (Figure 4). Given that temperature variations induce thermal stresses, this thermal field simultaneously functions as a stress field with a well-defined gradient.



**Figure 4.** Additional stress fields generated by high temperature and hot bodies in the crust (Image quoted from [10]).

When magma occurs in small volumes and thermal pressure is low, the surrounding rock undergoes slow creep—this process dissipates elastic stress and thereby prevents fracturing. If magma volume is substantial and thermal pressure is high, the creep of the surrounding rock cannot dissipate elastic stress sufficiently or promptly, resulting in continuous stress accumulation.

Typically, even as stress accumulates, rocks will not fracture as long as the accumulated stress remains below their failure strength. However, the accumulated stress diffuses outward, causing stress to build up in a larger area of crustal rock (**Figure 4**). When the energy from this accumulated stress grows sufficiently high—*i.e.*, when it reaches a critical state—an earthquake becomes imminent.

2) Triggering of Shallow Earthquakes. As long as the stress within a rock does not exceed its failure strength, the rock will not fracture and no earthquake will occur—regardless of how extensively that stress accumulates. Therefore, rock fracture only takes place when stress exceeds the rock's failure strength. However, even when rock fracture occurs, it does not necessarily produce a perceptible earthquake. For instance, the collapse of shallow rock cavities results from rock fracture, yet this phenomenon typically does not generate perceptible seismic activity. This is because the fractured area is extremely small, which releases only minimal energy. Consequently, perceptible or even major earthquakes occur exclusively when the fractured area is large and releases substantial amounts of energy.

If high stress accumulates simultaneously across a large rock mass, even a minor trigger can induce widespread rock fracturing. This process releases significant energy and thereby generates an earthquake. Specific triggering mechanisms include the following: 1) When magma rapidly expands in volume and rises in temperature, the resulting thermal pressure may exceed the surrounding rock's failure strength. This leads to extensive fracturing and ultimately triggers an earthquake. 2) Due to continuous heat transfer from magma to the overlying rocks, some of these rocks transition from a brittle to a ductile state. This transition causes a reduction in rock strength [5], followed by subsequent fracturing that generates earthquakes. 3) Due to the heterogeneity of crustal rocks and their strength, when stress accumulation extends to weak points like faults (**Figure 4**), fracturing occurs at these lower-strength zones. This ultimately triggers widespread rock rupture, resulting in earthquakes. Thus, earthquakes are caused by the long-term accumulation of energy and the sudden fracturing of localized rock.

Since the energy released by shallow earthquakes is entirely stored in rock, and a rock's energy storage capacity is positively correlated with its mechanical strength, the magnitude of an earthquake is also positively correlated with the mechanical strength of the rock at the hypocenter.

Generally, the mechanical strength of rocks is highest at depths of 10 - 20 km below the surface (**Figure 3**)—a key reason most high-magnitude earthquakes occur within this range. Mountain margins (*i.e.*, basin-mountain boundaries) are typically characterized by lower temperatures and higher pressures [14], resulting in rocks with the highest brittleness and mechanical strength. Consequently, these basin-mountain boundaries are prone to generating high-magnitude earthquakes.

In contrast, mountain interiors (e.g., mid-ocean ridges) have higher temperatures and lower pressures [14], producing rocks that are more ductile and have lower mechanical strength. Such regions can withstand less destructive energy, typically giving rise to lower-magnitude earthquakes. Additionally, due to the arching effect, the rocks at the base of the mountain (*i.e.*, the boundary between the mountain range and the basin) bear the greatest compressive stress [13] [25]. In the absence of magmatic activity, these rocks also exhibit the highest mechanical strength. If magmatic activity occurs within the crust beneath the foothills, an upward thermal stress simultaneously develops at the base. This generates immense shear forces on the foothill rocks. Concurrently, elevated temperatures and reduced rock strength make these shear forces highly likely to fracture the rock, triggering earthquakes. Consequently, the junction between mountain ranges and basins (or plains) is also a high-risk zone for seismic activity.

## 4.2. Formation of Deep Earthquakes

Although brittle fractures that generate earthquakes are unlikely to form in the ductile mantle, magma—a high-temperature mixture of gaseous, liquid, and solid phases—can undergo abrupt energy variations and phase transitions during its formation and migration within the upper mantle and asthenosphere. These processes may even trigger cryptoexplosions [11], thereby generating seismic events.

1) Thermal phase transition reactions can induce fractures that lead to earthquakes [11]. Certain materials undergo phase transitions under varying temperature and pressure conditions, which induce volume expansion or contraction that in turn triggers fractures and subsequent earthquakes. For instance, hydrated serpentine minerals dehydrate at temperatures exceeding 500°C, expanding in volume by 7.78% - 15.56%, whereas talc dehydration can induce a volume expansion of 0.72% - 4.12%. Numerous scholars have investigated such phase-change-induced seismic mechanisms, among which transformational faulting [1] stands as a prominent theoretical framework. This theory effectively accounts for seismic fracturing and slip phenomena. For example, the olivine-spinel phase transition induces fractures analogous to Griffith fractures but with opposing mechanical properties. When numerous such fractures interconnect and coalesce over time, they develop into faults. The superplastic nanoscale spinel grains that fill these reverse fractures function as fluid-like media, thereby facilitating the initiation of slip.

2) The massive production of hot gas triggers cryptoexplosion earthquakes. Seismic activity induced by cryptoexplosions is commonly attributed to high-energy fluids [11]. We propose that both high-energy fluids and magma originate from the melting of the upper mantle and asthenospheric materials—driven by radioactive heating induced by perturbations in atmospheric neutrino oscillations [12]. When the atmospheric neutrino flux is sufficiently high, when a region contains abundant radioactive materials, or when a region has significant volatile components (e.g., carbonates, sulfates, and hydrates), neutrino oscillations agitate these radioactive materials. This agitation induces the instantaneous release of immense thermal

energy, thereby vaporizing volatile components into large volumes of gases (such as  $H_2$ , He, CO,  $CO_2$ ,  $H_2O$ , and  $CH_4$ ). This process leads to rapid volumetric expansion and subsequent explosions, which in turn trigger earthquakes. The upper mantle is rich in carbonate rocks. When these rocks melt, they release significant volumes of  $CO_2$ . Under pressures exceeding 2.7 GPa ( $\sim 100$  km depth), this  $CO_2$  can only remain stably “dissolved” in carbon-rich magma. As the magma ascends and pressure drops, the  $CO_2$  in the magma undergoes exsolution, forming a supercritical  $CO_2$  phase [33]. Assuming a 40-km diameter sphere exists at depth with an initial  $CO_2$  pressure of 2.7 GPa and a volume fraction of 1%, the mechanical work performed by the sudden release of  $CO_2$  would be on the order of  $10^{22}$  J [34]. In the deep mantle with a pressure greater than 2.7 GPa, when the temperature suddenly rises, it can also cause rapid release of  $CO_2$  and generate mechanical energy.

Additionally, when hot magma ascends and accumulates in the crust to form magma chambers, the crystallization of certain minerals and interactions between magma and host rocks can also generate substantial amounts of volatiles. These volatiles drive rapid volumetric expansion, thereby triggering gas explosions that induce seismic events. Thus, earthquakes caused by cryptoexplosions can occur in both the mantle and the crust [11].

## 5. Discussion

### 5.1. Magmatic Activity and Earthquakes

Previous researchers have extensively studied the relationship between earthquakes and magma [6] [10] [11] [35]. Three key observations support this connection:

First, magmatic activity is a direct driver of volcanic eruptions. Since frequent earthquakes typically precede volcanic eruptions, this suggests that magmatic activity can also generate earthquakes [36] [37]. Second, major geological features such as mountain ranges, island arcs, and mid-ocean ridges are not only active zones of magmatic activity but also hotspots for seismic activity. Third, seismic activity frequently accompanies deep magmatic processes [6] [10] [11] [38].

Magmatic activity generates earthquakes by transferring substantial energy to the surrounding rock. Research indicates that magma reservoirs in the crust are typically crystal mush, generally ranging in volume from  $10^3$  to  $10^5$   $km^3$ , with melt content between 2% and 25%. For example, a magma reservoir at a depth of 5 - 10 km beneath Yellowstone National Park has a volume of approximately 4000 cubic kilometers with a melt fraction of 5% - 15%. At a depth of about 20 km, another larger magma reservoir exists with a volume of 46,000 cubic kilometers and a melt content of  $\sim 2\%$  [39] [40]. The initial temperature of magma generally does not fall below the melting temperature of the upper mantle ( $1300^\circ C$ ), while magma in the crust typically ranges from  $700$  to  $1200^\circ C$ . The heat lost as magma cools is largely absorbed by the surrounding rock. Assuming constant densities for both magma and host rock, with a specific heat capacity of  $C = 1000$  J/( $kg \cdot ^\circ C$ ) for the magma, a magma reservoir volume of  $V = 4000$   $km^3$ , and a reservoir density (*i.e.*, the crystal mush) of  $\rho = 2.7$   $kg/m^3$ , and the melt (or magma) content is

10% (average value), then when the magma temperature in the reservoir decreases from 1200°C to 700°C, the total energy released by the magma is:

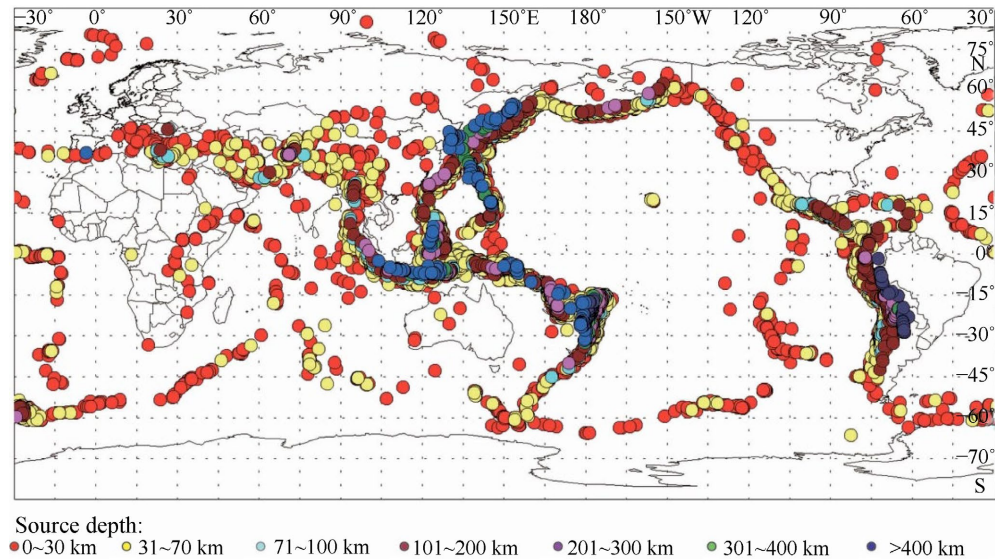
$$\begin{aligned} Q &= CM(T_1 - T_2) \\ &= 1000 \text{ J}/(\text{kg} \cdot ^\circ\text{C}) \times 4000 \text{ km}^3 \times 2.7 \text{ kg}/\text{m}^3 \times 10\% (1200^\circ\text{C} - 700^\circ\text{C}) \\ &= 5.4 \times 10^{17} \text{ J} \end{aligned}$$

where  $M = V\rho$ , representing the mass of the magma reservoir. Thus, if all the energy released by the magma contributes to earthquake nucleation and is released during the earthquake, it could generate a major earthquake of magnitude 8.9. If one-tenth of the energy contributes to earthquake nucleation, it could produce an earthquake approaching magnitude 8. In the above calculation, we assumed a magma temperature decrease of 500°C. In reality, when magma intrudes into the crust, the temperature drop can exceed 1000°C, releasing significantly more energy.

The theory of plate tectonics attributes the dynamic force (*i.e.*, energy source) of earthquakes to plate collisions or friction [5]. However, the driving mechanism underlying plate motion itself remains unclear [26] [27] [29]. Consequently, the true dynamic force responsible for earthquake occurrence has never been fully elucidated. This ambiguity has led many seismic theories to evade the fundamental question of earthquakes' ultimate energy source or force origin [27]. Currently, nearly all approaches—whether explaining shallow-focus earthquakes through the elastic rebound hypothesis [5] or interpreting intermediate- and deep-focus earthquakes via mechanisms such as dehydration embrittlement, thermal shear instability, fluid-induced fault motion models, and phase-change-triggered fracturing [1] [3] [4]—remain phenomenological [1]. Fundamentally, these approaches fail to address the core issue of energy and force sources [27]. All earthquakes—whether shallow, intermediate, or deep—ultimately originate from energy accumulation and force instability. The accumulation and driving force of magma (including fluids) can induce various changes and movements in rocks within Earth's interior, such as shear fracturing, phase transition fracturing, thermal expansion, and gas explosion fracturing. However, these rock fractures merely represent the manifestations of earthquakes rather than the dynamic or energy mechanisms underlying their formation. Therefore, in contrast to other earthquake theories, the proposed theory clearly identifies the energy source and elucidates the dynamic mechanism.

## 5.2. Causes of the Spatial Distribution of Earthquakes

Previous studies have identified distinct characteristics in the spatial distribution of earthquakes: Horizontally, most global earthquakes are concentrated along the Pacific Rim [9], while the remainder predominantly occur in orogenic belts and mid-ocean ridges (Figure 5). Vertically, the vast majority are shallow-seated earthquakes with focal depths of less than 70 km, whereas deep earthquakes reach a maximum depth that does not exceed the mantle transition zone (MTZ) [4]. Although the seismic mechanism governed by plate tectonics can generally explain the spatial distribution of earthquakes, it fails to account for intraplate earthquake formation.



**Figure 5.** Global epicenter distribution of 7959 earthquakes with magnitudes  $\geq 6$  in 1960-2016 (Image quoted from reference [1]).

This study demonstrates that the accumulation of seismic energy is primarily derived from magmatic activity. Rock fracturing—induced by crustal self-weight and magmatic thermal pressure, and ultimately triggering earthquakes—occurs exclusively within the brittle crust. Crustal thickness globally does not exceed 70 km, a value that also corresponds to the maximum depth of seismicity caused by brittle fracturing.

Given the low abundance of radioactive materials in the lower mantle, magma generation is highly restricted [12]. Magma primarily forms in the upper mantle, extending at most to the transition zone; thus, earthquakes triggered by phase transitions and gas explosions (both driven by high-temperature magma) can only occur within strata above the upper mantle and transition zone. This explains why earthquakes are generally absent from the lower mantle.

Beyond being constrained by crustal and upper mantle thickness, earthquake occurrence is further regulated by tectonic stresses and magmatic activity—factors that underpin the uneven lateral distribution of earthquakes globally. Once magma enters the lithosphere, its migration is primarily governed by stresses associated with surface arch-shaped tectonic processes, and it typically flows toward low-stress intermontane regions [13] [25]. Consequently, earthquakes driven by magmatic activity are generally concentrated in areas characterized by arch-shaped tectonic features, such as orogenic belts, island arcs, and mid-ocean ridges.

On a global scale, the Circum-Pacific seismic belt corresponds to a coastal zone dominated by mountain ranges and island arcs—an area also marked by intense magmatic activity. This explains why this region accommodates the vast majority of Earth's earthquakes. Notably, if magmatic activity occurs within a tectonic plate, earthquakes can also be triggered.

### 5.3. Anomalies of Cosmic Rays, Ionosphere, and Radon before Earthquakes

Earthquakes are often preceded by precursors or anomalous phenomena, such as radon activity, ionospheric disturbances, and thermal infrared anomalies [6]-[8]. Regarding the generation of seismic precursors (including electrical, magnetic, optical, acoustic, thermal, mechanical, and gaseous phenomena) by magmatic activity, Liu *et al.* [6] provided a comprehensive review, and other authors have also conducted numerous studies [1] [8]. We will not elaborate further on this here; instead, we focus on pre-earthquake anomalies in cosmic rays, the ionosphere, and radon.

Research has indicated a strong correlation between earthquakes and cosmic rays [2] [41]. Homola *et al.* [42] statistically demonstrated that variations in cosmic ray detection rates are correlated with global seismic activity, with a time lag of approximately two weeks. Yu [2] found that among the nine earthquakes with magnitudes exceeding 8 that have occurred in China since the 20th century, at least eight took place following an increase in cosmic ray levels. In addition, extensive research has shown that radon anomalies [7] [43] [44] and ionospheric anomalies [8] [45]-[47] also frequently occur prior to earthquakes.

Numerous explanations have been proposed for how cosmic rays might trigger earthquakes, such as inducing changes in the magnetosphere, ionosphere, and surface climate, or even triggering underground nuclear reactions—ultimately leading to seismic events [2] [42]. However, these explanations remain highly abstract, as no concrete mechanisms have been provided to validate them. Radon is a decay product of the radioactive elements uranium (U), thorium (Th), and radium (Ra). Previous researchers have generally believed that the accumulation and release of seismic energy induce changes in rock stress and geothermal conditions, which in turn lead to changes in radon emission rates from rocks and the solubility of dissolved radon in water, ultimately generating radon anomalies. Undeniably, these factors do contribute to radon anomalies; however, these mechanisms alone cannot explain the radon anomalies observed far from earthquake epicenters. Yan *et al.* [7] demonstrated that the rupture zone of the Wenchuan  $M_w 8.0$  earthquake had a length ranging from 240 to 400 km and a width of 15 to 25 km. Yet extensive radon anomalies were observed within the range of 500 to 900 km outside this rupture zone, and water radon anomalies were even detected as far as 1500 km away in locations such as Ningbo, Zhejiang Province. Clearly, such radon anomalies occurring far from the epicenter are difficult to explain solely by changes in rock stress and geothermal conditions. Ionospheric anomalies are more complex, characterized by both positive and negative anomalies in the total electron content (TEC). Although various models have been proposed to explain the formation of these anomalies [46] [48], these models still deviate significantly from the actual observed phenomena.

According to the mechanism elaborated in this paper, the aforementioned anomalies in cosmic rays, radon, and the ionosphere can all be reasonably explained (Figure 6). This is because atmospheric neutrinos are produced by the decay

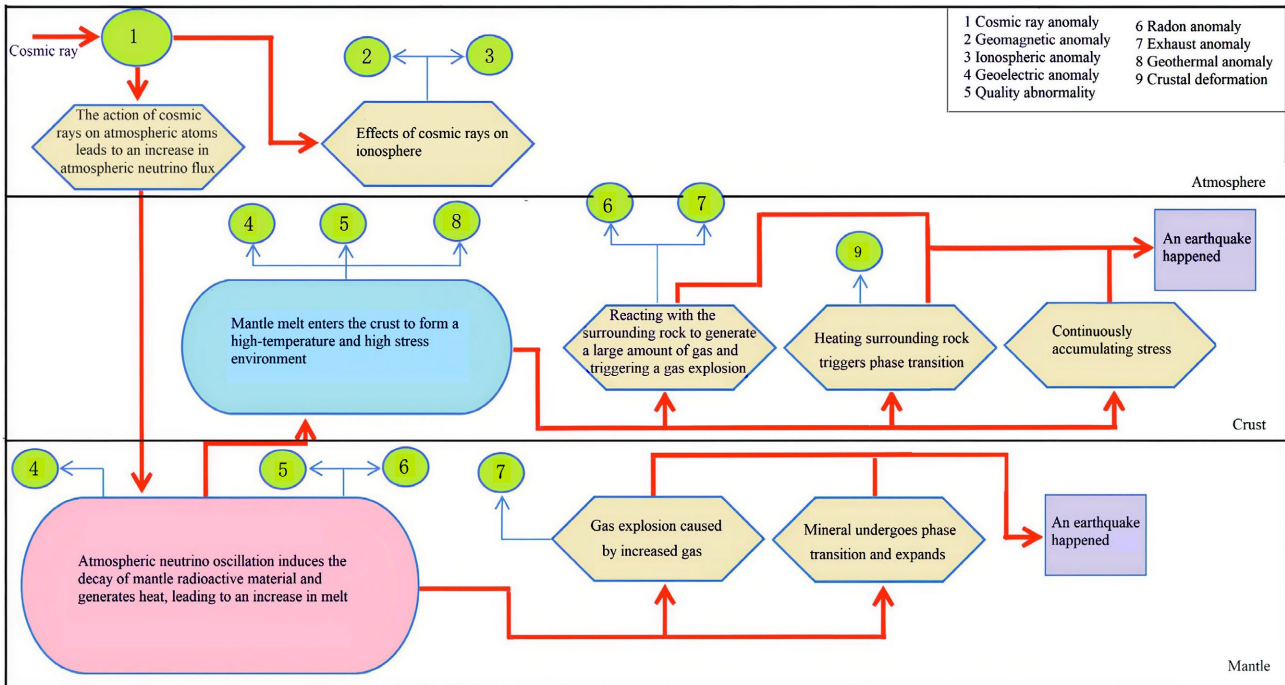


Figure 6. Correlation of some earthquake precursor phenomena.

of mesons—generated when cosmic rays collide with atmospheric atoms [12] [22] [23]—and elevated cosmic ray intensity increases the flux of atmospheric neutrinos. When high-flux atmospheric neutrinos resonate with matter via the MSW (Mikheyev-Smirnov-Wolfenstein) process, they exert a more significant influence on the excitation and decay rates of radioactive uranium (U), thorium (Th), and radium (Ra) [12]. This effect undoubtedly accelerates magma formation and induces anomalies in radon activity.

While variations in cosmic ray intensity across thousands of kilometers are fairly common, increased magma accumulation can only trigger earthquakes in regions where seismic activity is already mature. In other areas, it merely gives rise to radon anomalies (rather than seismic events). Additionally, cosmic rays are primarily composed of high-energy charged particles: positively charged atomic nuclei account for approximately 99% of this composition, and electrons for only about 1% [49]. When large quantities of cosmic rays penetrate the upper atmosphere, they neutralize and consume some atmospheric electrons. Meanwhile, interactions between cosmic rays (and secondary gamma rays) and atmospheric molecules/atoms induce ionization, generating a large number of electrons. Consequently, during cosmic ray surges, electron density in the upper ionosphere typically decreases due to neutralization (manifesting as a negative anomaly), whereas the lower ionosphere occasionally exhibits increased electron density (a positive anomaly)—driven by the ionization of the lower atmosphere by secondary gamma rays.

#### 5.4. Genesis of Pseudotachylite

Pseudotachylite is a type of solidified melt found within seismic fault zones, often

termed “seismic fossils”. It preserves critical physical and chemical information about seismic fault formation processes, acting as key carriers for deciphering the mechanisms underlying major earthquakes. Currently, two competing theories have been proposed to explain the origin of pseudotachylite. One theory posits that frictional heating along the fault plane induces mineral melting; upon cooling, the resulting melt solidifies together with residual clasts to form pseudotachylite. The other theory suggests that pseudotachylite is generated by hyperfracturing-pulverization processes [50]-[52]. However, neither mechanism adequately accounts for the coexistence of pseudotachylite and mylonite—their formation processes are, to some extent, mutually exclusive. Frictional melting and pulverization are typically pressure-dependent, representing rapid, high-strain, localized brittle processes. In contrast, mylonite formation is defined by the plastic deformation of minerals and typically occurs under non-seismic conditions [52].

Therefore, we propose that pseudotachylite forms when small volumes of deep magma are rapidly ejected along narrow fault-related fractures during earthquakes. This magmatic ejection takes place after an earthquake triggers the formation of such fractures, a stage when the fractures temporarily exist under near-vacuum, extremely low-pressure conditions. This mechanism enables pseudotachylite and mylonite to form simultaneously and coexist. It also effectively explains several observed phenomena: 1) the significant differences in chemical composition between the pseudotachylite matrix and the surrounding host rock; 2) the matrix being primarily composed of very fine-grained, angular clasts (devoid of friction marks); and 3) the distribution of pseudotachylite across varying depths within the lithosphere.

### 5.5. On the Issue of Earthquake Prediction

The most direct cause of earthquakes is stress accumulation exceeding the fracture strength of rock; all other factors are indirect. Therefore, to accurately predict earthquakes, it is essential to monitor in real time the strength and stress changes in the rock at the earthquake’s focal depth. However, humans currently lack the capability to monitor rocks at earthquake depths. Consequently, earthquake prediction can only be attempted indirectly through precursory phenomena. These precursors typically exhibit vast temporal and spatial scales—such as cosmic ray precursors, which span weeks to years temporally and thousands of kilometers spatially [2] [41]. Furthermore, cosmic ray intensification does not directly trigger earthquakes but rather leads to increased magma accumulation and the generation of thermal stress, which subsequently triggers seismic activity. Evidently, seismic activity and stress changes lag behind cosmic ray intensification. Therefore, utilizing these precursors—which exhibit significant spatio-temporal spans and delayed effects on earthquake triggering—makes it difficult to achieve precise earthquake prediction. Nevertheless, since earthquakes originate from magmatic activity, we can predict them by monitoring surface changes caused by underground magma migration (activity). This includes monitoring shallow stress (particularly vertical stress), geothermal temperature changes, and crustal deformation, while employing geophys-

ical methods to track deep magmatic activity. Although shallow stress and geothermal temperature may differ significantly from deep conditions, they may exhibit consistent trends. When combined with other earthquake precursors, this approach holds potential for accurate earthquake prediction.

## 6. Conclusion

This paper proposes an earthquake formation mechanism featuring clearly defined energy sources and driving forces. The primary energy source for earthquakes originates from atmospheric neutrino oscillations, which perturb radioactive elements in the Earth's interior to generate heat. This decay-induced heat can trigger partial melting of materials in the upper mantle and the asthenosphere, leading to magma formation. Driven by buoyancy, the magma rises into the crust, creating a high-temperature environment and exerting thermal stress on the surrounding rock—this in turn results in the continuous accumulation of stress within the host rock. When the accumulated stress exceeds the rock's fracture strength at a critical point, the rock fractures, thereby triggering an earthquake. Concurrently, deep-seated hot magma can induce phase transitions in minerals or trigger gas explosions; both of these processes are capable of generating seismic events. Of course, since the new theory of neutrino oscillation-induced radioactive decay and magma formation is merely a theoretical inference that has not yet been experimentally verified, it currently remains a hypothesis. Therefore, the mechanism proposed in this paper is only one perspective and awaits further research and testing.

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## Conflicts of Interest

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

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