

Matter Effect in Atmospheric Neutrino Oscillations and the Formation of Tektite

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Article

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Abstract: Tektites and microtektites are generally considered to be natural glasses formed when asteroids or comets collide with Earth, causing surface material in the impact zone to melt, be ejected into the air, and rapidly solidify. However, this impact origin theory is controversial because not all corresponding impact craters have been found and it is difficult to explain certain observational facts. Based on a new theory regarding neutrino oscillation-induced radioactive decay and magma formation, this paper explores water's matter effect in atmospheric neutrino oscillations and their thermal effects in deep-sea sedimentary layers. It proposes a new mechanism for the formation of tektites within deep-sea sedimentary layers and offers a reasonable explanation for a series of issues—such as the tektite age paradox—that the impact theory cannot resolve. This mechanism proposes that when seawater depth exceeds 1,500 m, atmospheric neutrinos can induce Mikheyev-Smirnov-Wolfenstein (MSW) resonance in seawater. Due to inertial effects, this resonance can maintain its resonant characteristics within seafloor sedimentary layers, thereby triggering the decay of radioactive materials within the sedimentary layers. This causes small regions enriched with radioactive isotopes to instantly generate a large amount of heat and rapidly melt, which then rapidly cools to form tektites. At the same time, this mechanism predicts a ^{40}K isotope deficit in tektites.

Keywords: Atmospheric neutrino • Neutrino oscillation-induced radioactive decay • Tektites • Formation mechanism • Sedimentary layer

Introduction

Tektites and microtektites are natural glassy melt rocks found on the Earth's surface, and they come in a wide variety of forms (Fig. 1). Tektites range in size from millimeters to centimeters and weigh from a few grams to several dozen grams, while microtektites are all smaller than a millimeter in size and weigh even less; apart from these differences, the two are virtually indistinguishable in terms of chemical composition and structural morphology¹⁻³. Therefore, unless otherwise specified, the term “tektites” used in this paper includes microtektites. Tektites exhibit a widespread yet restricted geographic distribution. Current research has identified five distinct tektite strewn fields: the North America strewn field (NASF), the Central Europe strewn field (CESF), the Ivory Coast strewn field (ICSF), the Australasian strewn field (AASF), and the Central America strewn field (Belize) (Fig. 2)^{1,3-6}.

Early researchers believed that tektites were extraterrestrial objects formed by volcanic eruptions on Mars (or the Moon) or impact events, before being scattered to Earth afterwards. Later studies revealed, however, that the chemical composition of tektites differs significantly from those of Mars and the Moon yet closely matches that of Earth¹⁻⁵,

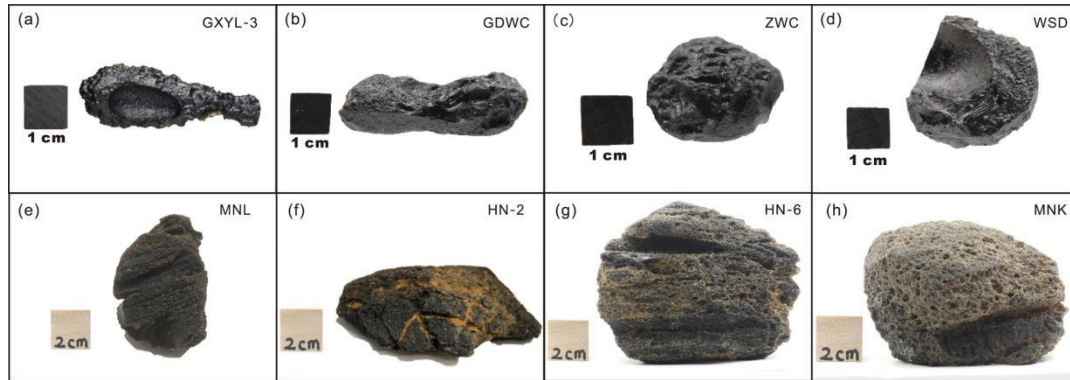


Fig. 1 Typical AASF tektites from South China. (a–d) Typical splash-form tektites with teardrop, rods and sphere shapes, and their fragments. (e–h) Muong Nong-type tektites from the Hainan Province. (Image quoted from Pan et al.³).

implying tektites originate from terrestrial materials. Based on existing geological evidence, the only natural terrestrial processes capable of generating natural glass are volcanic activity, lightning strikes, and hypervelocity impact events. Volcanic glass holds high water concentrations, with iron (Fe) predominantly occurring as hematite—properties entirely inconsistent with tektites, which are nearly anhydrous and host iron mainly as ferrous oxides^{1,7}. Furthermore, glassy rocks formed by lightning display internal textures, surface morphologies and chemical signatures drastically distinct from both volcanic glass and tektites⁸, so this formation pathway has also been eliminated. This leaves the impact hypothesis as the sole viable mechanism. Accordingly, the mainstream consensus holds that tektites form as ejecta during asteroid or comet impacts on Earth: the collision melts crustal/surface material, which is then launched skyward, quenches rapidly, and solidifies into glass^{9,10}. Nevertheless, the classical impact framework faces unresolved contradictions, as it cannot adequately account for the following key observations^{1,10–14}:



Fig. 2 Approximated geographic boundaries and source craters of the five major strewn fields of tektites on Earth. Figure modified from Li and ouyang², Pan et al.,³ and Soens et al.⁶

(1) Approximately 200 confirmed impact craters have been identified on Earth's surface, with diameters ranging from meters to hundreds of kilometers and formation ages

spanning 1 Ma to 2 Ga¹⁵. Tektites from different strewn fields share similar morphologies and physicochemical properties, implying a common, universal formation mechanism. This raises a key question: among all these impact events, why are only five major tektite strewn fields known to exist?⁴ Most tektites are also relatively young (post-Oligocene, 34–36Ma)^{1–3} with no confirmed older tektite deposits. Why did earlier impacts not form tektites? Most notably, why has no corresponding impact crater been found to date for the largest AASF, which covers approximately 10%–20% of the Earth's surface?^{3–6} And why did such a massive impact not result in a catastrophic mass extinction?^{1,16}

(2) The glass particles formed by impact should vary in size. Due to gravity, the larger, heavier tektites fall first; therefore, particles are larger the closer they are to the impact site, and smaller the farther away they are. For example, around the crater of a Chinese nuclear test, a large amount of molten glass generated by the nuclear explosion—with spatter-type features—was distributed as beads, buttons, gourds, rods, and dumbbells. Glass particle size decreased from 1.5 cm to 0.1 mm with increasing distance from the crater¹⁷. However, tektites within a single strewn field do not follow this size-distribution pattern. Studies show that within the AASF: the average diameter of tektites in the South China Sea is 0.35 mm (maximum 1 mm); samples from the Sor Rondane Mountains (SRM) in East Antarctica have an average diameter of 0.37 mm (maximum 0.57 mm); Indian Ocean specimens average 0.15 mm (maximum 0.65 mm)^{6,18}.

(3) Paleomagnetic data reported by Gattacceca et al.¹⁹ for Muong Nong-type tektites from southern Laos and northeastern Thailand show that their paleomagnetic inclinations relative to the stratigraphic plane cluster around an average value of $18 \pm 12^\circ$, consistent with the local paleolatitude. This finding indicates that Muong Nong-type tektites formed on the ground rather than in the air. In contrast, conventional impact-generated tektites cool and solidify while airborne, so they cannot acquire a magnetic inclination matching that of their host geological environment^{3,20}.

(4) In the field, age scatter is commonly observed among tektites within the same strewn field. For the Australian strewn field, the widely accepted formation age spans 0.78 Ma to 0.80 Ma; nevertheless, numerous studies have documented tektites yielding disparate ages^{2,21–23}. In particular, a set of ages ranging from 7 to 24 ka, derived from stratigraphic dating^{14,24,25} highlights the age paradox of tektites. Earlier workers attributed this offset to secondary sedimentary transport²⁴; however, large-scale secondary reworking of this magnitude is geologically implausible. Moreover, field observations demonstrate that most tektites lack surface erosional features, confirming they underwent no post-emplacement transport¹⁴. Furthermore, tektites occur in multiple stratigraphic horizons at a single locality, covering a broad temporal interval. Hazel's work²⁶ documented a minimum of six tektite-bearing horizons dating to the Late Eocene. In deep-sea sediment cores recovered from tektite-bearing areas off Australia and Côte d'Ivoire, tektites occur throughout a 35–90 cm vertical sediment interval, corresponding to a depositional duration of 100 ka²⁷.

(5) Australian strewn-field tektites fall into three morphological types: classic splash-form tektites, flanged or ablated forms bearing remelting textures, and layered or Muong Nong-type tektites. Regarding the genesis of flanged or ablated tektites, early investigators proposed that some tektites were lofted into the upper atmosphere prior to re-entry into the atmospheric column. Aerodynamic ablation, driven by atmospheric

compression, acted on the forward surfaces of these spherical bodies, ultimately producing flanged specimens capped by an enamel crust^{1,12,14,25,28}. Numerical simulations show that secondary ablation of tektites requires extremely high initial velocities and an exceptionally tenuous atmospheric envelope^{12,13} — conditions incompatible with Earth's actual atmospheric environment. Furthermore, existing models cannot offer a satisfactory mechanism to explain coesite formation and the internal layering characteristic of Muong Nong-type tektites^{4,19,20,29,30}.

Given the limitations of the impact theory, we hold that exploring alternative hypotheses constitutes a valuable effort to advance academic discourse and ultimately unravel the formation mechanisms of tektites. In recent years, Zhang and Zhang^{31–33} proposed that the Mikheyev–Smirnov–Wolfenstein (MSW) mechanism of atmospheric neutrino oscillations^{34–36} may trigger radioactive decay and the subsequent melting of silicate materials. They contend that mantle melt arises from radiogenic heat production modulated by the MSW mechanism. Accordingly, in natural systems, alongside volcanic activity, lightning strikes, and impact events, radiogenic heat perturbed by the MSW mechanism can also induce melting and glass formation. This study applies this novel melt-formation theory to construct a new model of tektite genesis. Building upon prior tektite research, the MSW neutrino oscillation mechanism^{34–36}, and recent melt-generation theories^{31–33,37}, this work examines atmospheric-neutrino-driven MSW resonance in seawater and its impacts on underlying sedimentary strata. A tektite formation mechanism within deep-sea sedimentary sequences is proposed, offering a self-consistent account of several long-standing discrepancies that the impact theory struggles to reconcile.

Results and Discussion

The formation mechanism of tektites

Previous studies have shown that the source rock of tektites is sedimentary strata^{1,3}. The main evidence supporting this conclusion includes: 1) The chemical composition of tektites—including the abundances and ratios of major and trace elements, as well as isotopic data—is highly consistent with that of sediments^{1,38,39,40}. 2) The rare earth element abundances in tektites resemble those in sedimentary rocks^{41,42}. 3) Inclusions observed in Muong Nong-type tektites, such as zircon, rutile, monazite, chromite, quartz, and aluminosilicate minerals, indicate that these tektites formed from clastic sedimentary material^{1,43,44}. 4) Residues suspected to be biomatter have been identified in a small number of tektites^{45,46}. Therefore, the fact that tektites originate from sedimentary rock is one of the key constraints in theories regarding their formation^{3,15,30}. If atmospheric neutrinos can induce MSW resonance as they pass through the sedimentary layer, radioactive material within the layer may be perturbed by the resonance and undergo decay, thereby causing some of the material to melt. However, since the sedimentary layer consists of terrestrial clasts, biological remains, volcanic ash, water, and gases, its density is highly heterogeneous. It is therefore difficult to satisfy the conditions required for MSW resonance in neutrino oscillations—namely, a constant material density and a width greater than 1,500 m^{33,37}—so atmospheric neutrinos generally cannot produce MSW resonance within the sedimentary layer. However, if the thickness of the seawater

overlying the sedimentary layer exceeds 1,500 m, atmospheric neutrinos can form an MSW resonance in the seawater. At the same time, owing to inertial effects, this resonance can perturb the sedimentary layer beneath the seawater, causing radionuclides within the sedimentary layer to be resonantly excited and produce heat via decay³⁷(Fig. 3). Macroscopically, radioactive materials are uniformly distributed within sedimentary layers; microscopically, however, small domains exist where certain radioactive elements are relatively concentrated, for instance low-energy reducing zones containing monazite, K-feldspar, and organic matter^{46–50}. Perturbed by MSW resonance arising from neutrino oscillations, these micro-domains enriched in radioactive elements can instantaneously generate large amounts of decay heat, resulting in complete melting of local materials. The thermal history of tektites constrains their cooling rate to a few °C/s⁵¹, which agrees with the critical cooling rate of 1–10 °C/s for glass formation from silicate melts. Accordingly, melts are quenched to form tektites when the cooling rate surpasses this critical value(Fig. 3).

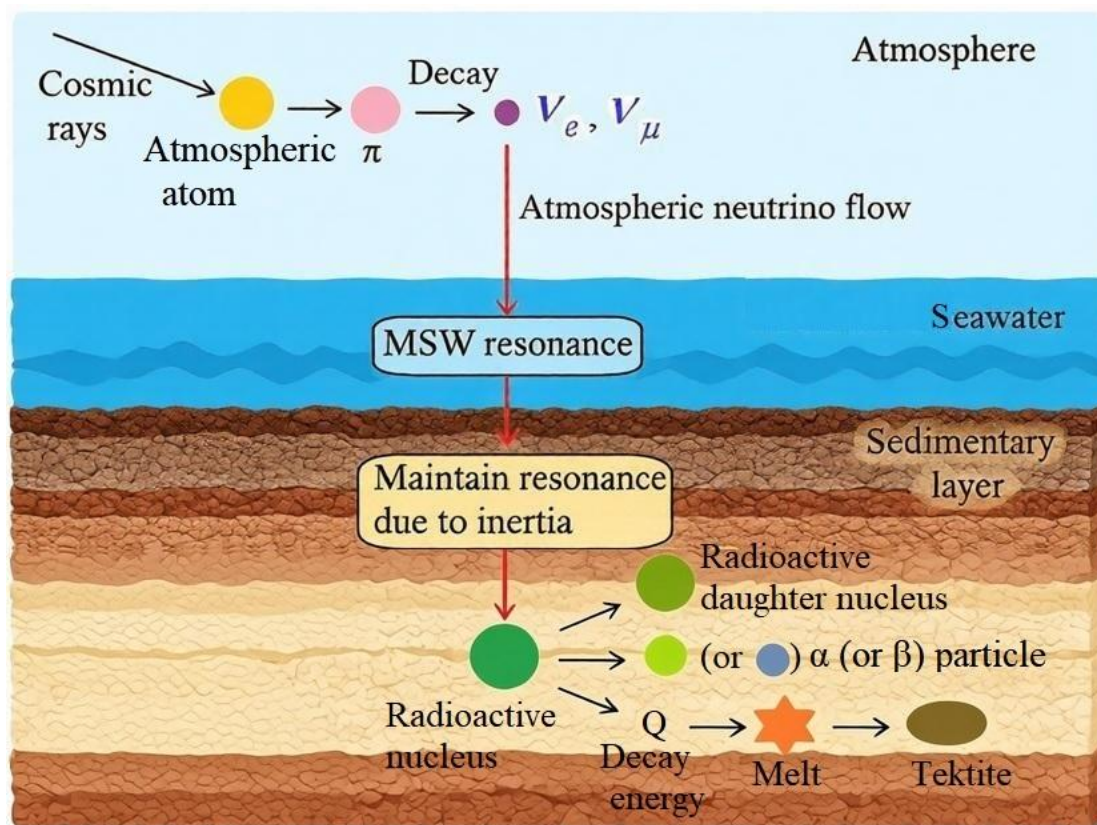


Fig. 3 Atmospheric neutrinos induce MSW resonance in seawater of constant density; due to inertial effects, this resonance is maintained within the sedimentary layer, where it disrupts the decay of radioactive elements, causing localized melting and subsequent rapid cooling to form tektites.

Heat sources for the formation of tektites

There are regional variations in the abundances of the major radioactive elements U, Th, and K within marine sedimentary layers, but overall these values are comparable to those of the Earth's crust. The average crustal abundances of U, Th, and K are 2.07×10^{-6} , 7.60×10^{-6} , and 1.93×10^{-2} , respectively⁵². In sediments of the South China Sea proximal

to the mainland (encompassing the continental shelf, continental slope, and oceanic basin), the abundances of the radioactive elements U, Th, and ^{40}K are 2.05×10^{-6} , 9.47×10^{-6} ⁵³, and 2.85×10^{-6} (corresponding to a K_2O content of 3.0%)⁵⁴, respectively. The abundances of U and Th in marine sediments from the Red Sea off the Egyptian coast are 2.23×10^{-6} and 2.15×10^{-6} , respectively⁵⁵. The U and Th abundances in brown clays of the western Pacific Ocean are 1.60×10^{-6} and 9.00×10^{-6} , respectively⁵³. In some sediments containing biogenic apatite fossils, radioactive elements are enriched, yielding relatively high abundances; examples include the Tiki Basin (TKB) in the southeastern Pacific and the Central Indian Ocean Basin (CIOB). The U, Th, and ^{40}K abundances in the TKB are 3.25×10^{-6} , 6.61×10^{-6} , and 2.22×10^{-6} , respectively ($\text{K}_2\text{O} = 2.33\%$); in the CIOB, U, Th, and ^{40}K abundances are 2.19×10^{-6} , 19.6×10^{-6} , and 2.59×10^{-6} , respectively ($\text{K}_2\text{O} = 2.72\%$)⁴⁷.

Tektites are commonly associated with reducing materials such as phosphorite and organic matter^{46,48–50}, and sediments enriched in these reducing components often show elevated concentrations of radioactive elements⁴⁷. Therefore, the radioactive element abundances of tektite source rocks are higher than those of other sediments. Studies^{1–3,14,56} have demonstrated that tektites are enriched in radioactive elements, with total radioactivity approaching that of granite. If radioactive decay provides the heat source for tektite formation, then during high-temperature melting of the source rock to form tektites, some radioactive elements are depleted via decay, whereas other volatile radioactive elements — such as U and K — are lost through distillation. Consequently, the radioactive element concentrations of tektite parent rocks should be substantially higher than those measured in tektites themselves.

Tektites typically range in mass from a few grams to several tens of grams. We calculated the heat required to form a 50-g tektite. This heat mainly corresponds to the energy needed to melt an equivalent mass of sediment. Deep-sea microtektites are commonly recovered from siliceous mudstone; we therefore assume that these tektites formed via melting and rapid cooling of siliceous mudstone on the seafloor. The specific heat capacity of siliceous mudstone is 0.82–0.90 kJ/(kg·°C), and we adopted an average value of 0.86 kJ/(kg·°C). Its melting point varies substantially with mineral composition; the most refractory constituent, silicon dioxide, requires a temperature of 1700 °C for complete melting. We thus set the temperature for full melting of siliceous mudstone to 1700 °C, and the temperature of seafloor sedimentary layers to 10 °C. Using the formula $Q = C_p M (T - T_0)$ (where C_p is the specific heat capacity, and M is the mass of the rock as its temperature rises from T_0 to the melting point T), the heat required to melt 50 g of siliceous mudstone is calculated as $7.27 \times 10^4 \text{ J}$. The heat produced by radioactive decay can be calculated from the decay equation³¹:

$$E = N_A \frac{M}{g} Q \quad (1)$$

where M is the mass of the radioactive isotope, g is its molar mass, $N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$ is Avogadro's number, and Q is the energy released per decay of the radionuclide. Based on the abundances of radioactive elements in South China Sea sediments (i.e., U, Th, and ^{40}K at 2.05×10^{-6} , 9.47×10^{-6} , and 2.85×10^{-6} , respectively^{53, 54}), and using Equation (1), it is calculated that the heat generated by the complete decay of U, Th, and

^{40}K in 50 g of sediment is approximately $1.10 \times 10^7 \text{ J}$. The energy required to melt 50 g of sediment accounts for only 0.66% of the total decay energy. In other words, the decay of just 0.66% of the radioactive elements in sedimentary rock is sufficient to provide the heat required for the formation of tektites.

The role of temperature and pressure in the surrounding rock in the formation of tektites

The cooling rate determines whether a melt can form a tektite, and the cooling rate of the melt is strongly controlled by the temperature and pressure of the surrounding rock⁵⁷; therefore, ambient temperature and pressure play a critical role in tektite formation. The time required for a siliceous melt to cool from 1700 °C to its glass transition temperature T_g ($T_g \approx 780$ °C for silicon-rich silicates⁵¹) is governed by thermal diffusion. The thermal diffusivity of silicates, D_{th} , is approximately $10^{-6} \text{ m}^2/\text{s}$. For a melt body with a diameter of 1 mm, the cooling time τ can be estimated using the general relation $\tau = r^2/D_{th}$, yielding $\tau = 1$. Accordingly, the cooling rate is $dT/d\tau = (T - T_g)/\tau = (1700 \text{ °C} - 780 \text{ °C})/1 \text{ s} = 920 \text{ °C/s}$. This value is far higher than the critical cooling rate required for glass formation in silicate melts. This indicates that a 1-mm-sized melt can readily quench to form glass. If the melt dimension increases to 20 mm, the corresponding cooling rate falls to 2.3 °C/s. Typically, the cooling rate at the melt exterior exceeds that in the interior; under this condition, crystals may precipitate within the melt owing to slower internal cooling. This explains why crystalline minerals are commonly observed in larger Muong Nong-type tektites^{1,30,46}.

Most oceanic crust and a small fraction of the lithospheric mantle have temperatures below the glass transition temperature T_g ; hence, melts produced within the oceanic crust and lithospheric mantle can also be quenched to form glass. At identical temperature and pressure conditions, the thermal diffusivity of oceanic crust and lithospheric mantle rocks is very close to that of silicon-rich silicates. However, thermal diffusivity generally decreases linearly with rising temperature⁵⁷; as a result, mafic melts within warmer domains of the oceanic crust and mantle cool more slowly and tend to crystallize. Consequently, glasses formed in the oceanic crust and mantle are mostly associated with mafic or ultramafic minerals (e.g., olivine, amphibole, and biotite). In addition, compared with unconsolidated sedimentary mud layers, the lithosphere is rigid and effectively sealed. Volatiles released during melting (including gaseous species such as H_2O and CO_2 , and volatile elements such as Na and K) are often trapped within the host rock, establishing a high-pressure environment that increases volatile solubility in the melt. Therefore, glasses formed in the oceanic crust and mantle are commonly intergrown with mafic minerals and enriched in volatiles; these features are generally described as melt inclusions or melt pockets^{31,58,59}.

Between sedimentary layers and the basaltic oceanic crust lie metamorphic rock layers whose hardness and impermeability fall between those of mudstone and basalt. Consequently, the glassy inclusions formed in this intermediate layer have a mineral composition similar to that of tektites—for example, containing quartz crystals—but their volatile content is closer to that of melt inclusions. Consequently, the composition and morphology of the glass formed in metamorphic rock layers more closely resemble volcanic glass. It is highly likely that the Cali Glass⁶⁰ formed within the metamorphic rock layers.

Muong Nong-type tektites

Muong Nong-type tektites exhibit characteristics such as layering, high volatile content, and the presence of inclusions; these features also place constraints on tektite formation. The mechanism proposed in this paper satisfactorily satisfies these constraints.

First, layered structure and high volatile content. Given that Muong Nong-type tektites are generally large, the author proposes that some of their properties may originate from the high potassium-feldspar content of their source rocks. Potassium feldspar lowers the melting temperature, enabling a limited amount of heat to melt greater volumes of sediment, which then solidifies rapidly to form larger tektites. Owing to the low formation temperature^{30,61}, the melt possessed high viscosity, and the molten sedimentary rock solidified rapidly with negligible flow after melting. Consequently, the resulting tektites preserve the layered fabric of the parent sedimentary rock (Fig. 1)^{3,46,48}; Muong Nong-type tektites are therefore effectively metamorphic glass. This also explains the high volatile contents (including water) and occurrence of metamorphic components within Muong Nong-type tektites^{7,9,46,48,62}.

Second, coesite and froth layers. Muong Nong-type tektites contain coesite associated with froth layers^{30,63-65}. Coesite is a high-pressure phase; therefore, some authors cite it as evidence supporting the impact hypothesis^{30,64,65}. The solid-state transformation of quartz into coesite represents a slow crystal-restructuring process, and high-pressure pulses generated by impacts are too brief (a few microseconds) to drive solid-state conversion of quartz to coesite. Consequently, it is generally accepted that coesite in tektites (or impact glass) forms via crystallization from an amorphous phase. This includes coesite crystallization from impact-produced silicate melt during impact unloading, as well as solid-state transformation of birefringent quartz glass⁶⁴. However, studies have demonstrated that coesite formation within tektites can involve direct subsolid-state transformation from quartz to coesite^{64,66}. Accordingly, some authors have proposed a mechanism for direct subsolid-state quartz-to-coesite transformation upon shock-wave reflection^{30,65}. This mechanism assumes that pressure-pulse durations for natural impacts exceed those achieved in shock-recovery experiments⁶⁶. This article does not discuss the validity of this assumption here. Instead, the author emphasizes that, within the shock-theory framework, even if coesite were formed, its preservation poses a major challenge. Coesite is thermodynamically unstable at high temperatures and tends to revert to orthoclase. Porphyritic inclusions in Muong Nong-type tektites indicate peak temperatures exceeded 1700 °C (the melting point of pure SiO₂). During impact unloading, before temperatures decline to the tektite liquidus (~1130 °C), coesite would convert to the thermodynamically more stable orthoclase. Hence, the preservation of coesite inside tektites remains highly enigmatic^{30,65}.

There is a froth layer surrounding coesite inclusions. Glass et al.³⁰ suggest that this froth layer may be the decisive factor for the preservation of coesite within the inclusion core, because foam formation consumes energy and rapidly lowers the temperature of the inclusion. Masotta et al.⁶⁵ propose that the froth layer originates from the dissociation of H₂O molecules and rapid dissolution of their atomic constituents (predominantly H₂). However, H₂O dissociation generates substantial quantities of O₂, which is inconsistent with the occurrence of low-valent iron oxides (Fe²⁺) in tektites. Based on the presence of

Ne⁶⁷ and Ar⁶⁸ in the decay products of U, Th, and K, as well as the enrichment of noble gases such as Ar and Ne in the vesicles of Muong Nong-type tektites⁶², the author proposes that coesite forms in tektites as a consequence of repeated MSW-resonance perturbations. Muong Nong-type tektites have large volumes and cool slowly, frequently leading to the precipitation of crystals such as quartz and mica^{1,46,48}. Upon further disturbance by MSW resonance, ⁴⁰K-rich domains within Muong Nong-type tektites instantaneously release large quantities of heat and generate gases; these gases nucleate and expand to form bubbles, establishing an autoclave-like environment inside the tektite. This facilitates the gradual solid-state transformation of quartz to coesite under sustained high pressure (Fig. 4). At the same time, the noble gases produced during the initial melting are more likely to escape from the melt, whereas the subsequent melting occurs within the tektite, causing the noble gases produced to be largely trapped inside it. This explains why the bubbles in Muong Nong-type tektites are enriched in noble gases such as Ar and Ne⁶². When energy released by secondary MSW-resonance perturbation is sufficiently high, complete shattering of the tektite may occur⁶⁹.

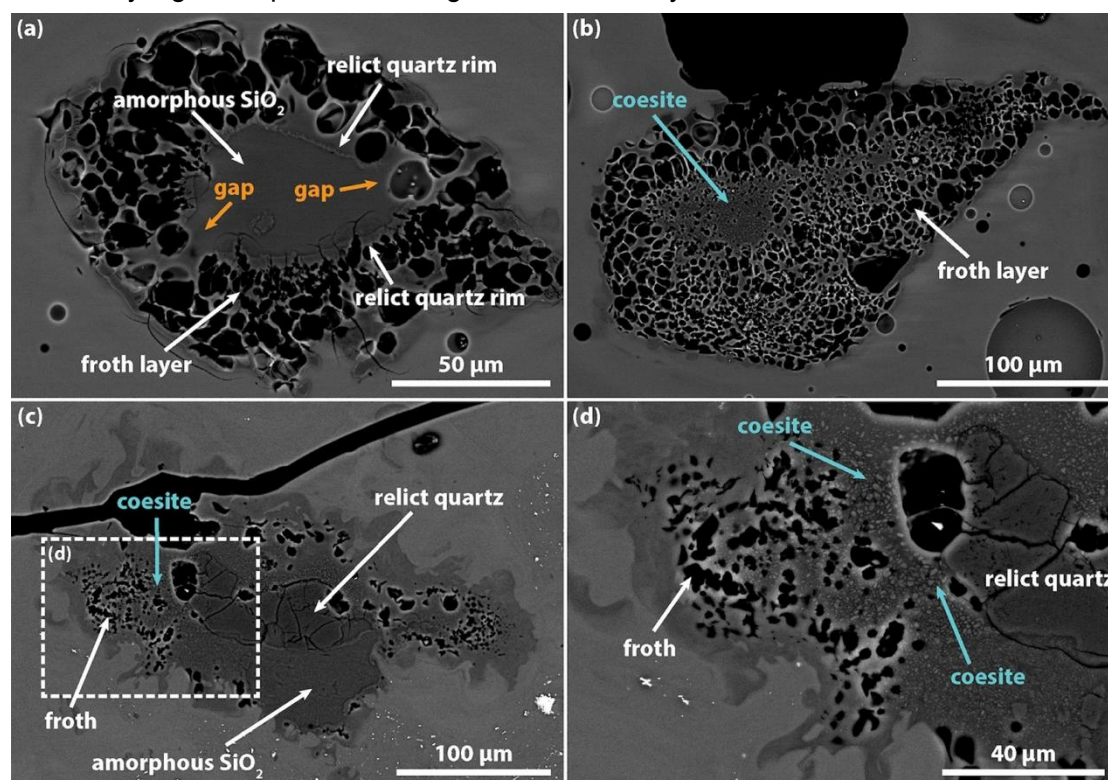


Fig. 4 Backscattered electron images of the froth layer and coesite in atektite (Image quoted from Masotta et al.⁶⁵).

Third, bright halos. Glass et al.³⁰ documented newly precipitated quartz crystals and associated bright halos surrounding the froth layer. Within these bright halos, K₂O is depleted by approximately 50 %, whereas concentrations of other oxides exhibit only minor variations. Those authors interpret this feature as a product of intense reverse diffusion. Nevertheless, for reverse-diffusion processes, alkalis (e.g., K₂O) typically diffuse upward from crystal boundaries into the more highly polymerized melt, rather than diffusing outward from the halo melt into the more polymerized host tektite melt⁷⁰. Drawing on the mechanism outlined in this paper, the author proposes the following: when a K-(or

U, Th) -rich microdomain is perturbed by MSW resonance, its temperature rises and a bubble forms. Some microdomains adjacent to the bubble layer are also subject to MSW-resonance perturbation. Although their K contents are moderately lower and the released heat is inadequate for volatiles to coalesce into bubbles, the heat input is enough to induce local remelting of the tektite. Since K-bearing domains represent the hottest zones, K diffuses toward cooler adjacent regions, generating a bright halo. Subsequent cooling of the melt triggers crystallization and produces secondary quartz.

Explanations of Some Other Issues

(i) Remelting. Although tektites form through the depletion of some radioactive materials, some still contain high levels of radioactivity. Therefore, when a tektite rich in radioactive materials is once again disturbed by MSW resonance, it may remelt. During the initial melting, radioactive elements diffuse from the high-temperature, enriched regions toward the lower-temperature edges, resulting in relatively higher radioactive enrichment at the edges of the tektite. Additionally, heavy radioactive elements such as U and Th sink to the very bottom of the tektite. Consequently, remelting occurs only at the radioactivity-enriched edges and bottom, leading to the formation of button-like morphologies capped by a flanged crust^{14,28}. At the same time, the production of additional argon during remelting results in higher apparent ages for remelted tektites¹⁴.

(ii) The age paradox. Since tektites form when neutrino oscillations accelerate the decay of radioactive elements, generating heat and inducing rapid cooling, some radioactive daughter products become rapidly trapped within the tektite and cannot escape. Therefore, the age of a tektite measured by the K–Ar method is not its true age but its apparent age. As calculated earlier, the decay of just 0.66% of the radioactive elements is sufficient to melt the sediment. If 0.66% of the ⁴⁰K had also decayed at the time the tektite formed, and all the argon produced by ⁴⁰K decay was trapped within the tektite, then the apparent age resulting from the decay of 0.66% of the ⁴⁰K would be 11.9 Ma. Tektites cool extremely rapidly, making complete argon escape difficult; a portion is trapped within the tektite¹⁴, giving rise to the apparent age of the tektite. By the same token, the apparent age corresponding to 0.66% depletion of ²³⁸U is 42.7 Ma. Because tektites form via melting of sedimentary material, their true age cannot exceed the age of the host strata. The youngest stratigraphic age for tektites in the Australian strewn field is 7 ka²⁵; accordingly, the true age of tektites formed within this stratum is no older than 7 ka. Apparent ages of tektites vary among different strewn fields and even within a single strewn field^{1–3,14,21–25,50}, which may be attributed to the following factors: 1) differences in timing of formation; 2) variations in cooling rate during formation (i.e., argon closure); 3) differences in radioactive element abundance of the original sedimentary matrix; and 4) other unconstrained factors¹⁴.

(iii) The absence of early tektites. Based on the mechanism described in this paper, the author proposes that the reason no tektites predating the Eocene have been discovered to date may be due to the following factors: 1) Tektites form when molten material undergoes rapid cooling, a process that can only take place within loose sedimentary layers. Once sedimentary layers become compacted and metamorphosed and are no longer loose, molten material cools slowly within the surrounding rock owing to the rock's high heat-retention capacity. Under such conditions, crystalline minerals form, or the

material undergoes metamorphism together with the host rock, instead of producing tektites. 2) After tektites are formed, seafloor subsidence may thicken, compact, and metamorphose the host sedimentary layers. Pre-existing tektites will then experience devitrification and crystallize into minerals. Consequently, when the seafloor is uplifted and exposed subaerially, no tektites survive. 3) Preservation of tektites requires tectonically driven seafloor uplift and subaerial exposure shortly after tektite formation and prior to substantial compaction or metamorphism of the host sedimentary layers. Nevertheless, the tektite-bearing sedimentary succession remains loose at this stage, so tektites are readily altered by seawater, resulting in devitrification. Even if a small number of tektites survive intact and are exposed above sea level, they are highly vulnerable to weathering and abrasion during transport. Only larger tektites can be preserved, which explains why most tektites recovered on land are comparatively large. These large terrestrial tektites were derived from ancient marine sedimentary layers. Some tektites with continental substrates may have formed on continental slopes⁴⁶ at water depths greater than 1500 m, or they may represent specimens collected by humans (e.g., tektites found in terrestrial strata in Baise, Guangxi, China^{71,72}).

Furthermore, why are there no AASF impact craters^{1–3}? Why does the size-distribution pattern of tektites lack apparent regularity^{6,17,18}? Why do tektites display magnetic inclinations consistent with the latitudes of their host environments^{3,19,20}? Why do tektites possess compositions resembling those of near-surface sedimentary layers^{1–3,46}? The mechanisms proposed in the present paper offer satisfactory explanations for these observations, and therefore further elaboration is omitted here.

Preliminary Evidence and Existing Issues

(1) The environment in which tektites are found is consistent with the mechanism described in this paper. To date, nearly all tektites have been recovered from sedimentary layers^{1–6,24–27,73,74}. Microtektites discovered in deep-sea settings are almost exclusively found within loose, muddy sediments near the tops of these sequences^{4,14,46,56,75}. For example, microtektites in the North Pacific occur in calcareous mud and silico-calcareous mud; those from deep-sea sediments of the Central Pacific are associated with surficial red clay, siliceous mud, calcareous mud, or silico-calcareous mud⁷⁶; and in the East Pacific, microtektites in DSDP Site 573 cores occur at the base of a metal-bearing clay layer⁷⁷. In addition to microtektites, these diverse sediments contain abundant biogenic remains—such as foraminifera, radiolarians, and turtle teeth—as well as volcanic clasts and manganese nodules^{76,78}. Tektites exposed subaerially, on the other hand, are typically found within weathered clay^{63,69,79}. It is particularly noteworthy that the seawater from which microglass meteorites were recovered in deep-sea sedimentary layers all originated at depths exceeding 1,500 meters^{75,77,78}. This is highly consistent with the minimum width required for the MSW resonance triggered by neutrino oscillations³⁷. For example, some microtektites in the Indian and Pacific Oceans are concentrated in sedimentary layers at seawater depths of 2900–4910 m^{50,75,77,78}. Microtektites recovered by Chinese researchers in the deep waters of the western Central Pacific occur in sedimentary layers at seawater depths of 2000–5000 m⁷⁶; in the eastern Pacific, microtektites from DSDP Hole 573B cores were found at seawater depths exceeding 4300 m⁸⁰; and in the deep sediments of ODP Site 1170, Hole B in the South Tasman Sea,

microtektites were identified in sediment layers at seawater depths exceeding 2705 m⁸¹. Several drill sites in the South China Sea containing microtektites have relatively shallow seawater depths. Microtektites from ODP Hole 1144 were primarily recovered in sediment layers at seawater depths exceeding 2037 m^{40,82}, while microtektites in core 17957 from the northern Nansha waters of the South China Sea were found in sediment layers at seawater depths exceeding 2195 m⁸³. ODP Hole 772A records the shallowest seawater depth, at approximately 1529 m, with a drill-core penetration of 360 m⁷⁷.

(2) The loss of radioisotopes is consistent with the mechanism described in this paper. During the formation of tektites, radioactive isotopes such as ⁴⁰K undergo accelerated decay due to MSW resonance perturbations, leading to excessive decay and depletion of the parent nuclide, while daughter nuclides (e.g., argon)^{5,84,85} become relatively abundant. The excess argon in tektites does not originate from external sources but is produced by the decay of ⁴⁰K. Therefore, ⁴⁰K must be depleted in tektites. To date, no published research has reported whether ⁴⁰K is depleted in tektites. Although high-temperature fractionation reduces the light isotopes of potassium, depletion of the heavy isotope ⁴⁰K caused by accelerated radioactive decay may reach several percent. In contrast, light-isotope depletion driven by fractionation is less than one-thousandth⁸⁶; thus, ⁴⁰K depletion should be measurable. In addition to ⁴⁰K, another radioactive isotope in tektites, ⁸⁷Rb, should also show depletion. Deng et al.⁸⁷ measured the Rb isotopic compositions of tektites, reporting $\delta^{87}\text{Rb}$ values ranging from $-0.22 \pm 0.05\text{‰}$ to $-0.12 \pm 0.03\text{‰}$, with an average of $-0.16 \pm 0.06\text{‰}$ (2SD, $n = 14$). This average is marginally lower than the upper-continental-crust value ($\delta^{87}\text{Rb} = -0.14 \pm 0.01\text{‰}$), indicating a slight ⁸⁷Rb deficit. Rb, Cu, Zn, Sn, and Pb are moderately volatile elements (MVEs). Previous studies have demonstrated that Cu, Zn, Sn, and Pb in tektites exhibit heavy-isotope enrichment following evaporative depletion^{86,88-90}. Contrary to this pattern, ⁸⁷Rb shows slight depletion rather than enrichment, constituting a geochemical anomaly. Deng et al.⁸⁷ proposed that this anomaly could arise from suppressed Rb-isotope fractionation during impact-driven evaporation under Earth's oxidizing near-surface conditions. However, this interpretation requires re-evaluation, given that tektites form under reducing conditions. Based on the tektite-formation mechanism proposed herein, the author interprets that accelerated ⁸⁷Rb decay counteracts the loss of the lighter ⁸⁵Rb isotope produced by evaporation-driven isotopic fractionation.

In summary, multiple features of tektites — including their layered structure^{3,46,62}, occurrence of breccia²⁹, and nearly horizontal magnetic dip angle^{19,20} — indicate that they experienced in-situ melting. Meanwhile, excess argon^{3,5,84,85} and ⁸⁷Rb depletion in tektites suggest excessive depletion (accelerated decay) of radioactive ⁴⁰K and ⁸⁷Rb. All these observations support the mechanism proposed in this paper. Nevertheless, these constitute only indirect evidence. Because the foundational basis of our proposed mechanism relies on a theory that has not yet been experimentally validated, this mechanism remains a theoretical hypothesis requiring experimental verification. Accordingly, future work could test whether ⁴⁰K is depleted in tektites and whether radioactive decay is accelerated at water depths greater than 1500 m, to falsify or validate the theoretical hypothesis presented here.

Methods

Radioactive decay induced by neutrino oscillations

Wolfenstein³⁴ and Mikheyev and Smirnov^{35,36} successively studied neutrino oscillations in matter and established the evolution equations governing the propagation of neutrinos through matter. By solving these equations, they derived the neutrino flavor conversion probabilities. For convenience, we will use the oscillation between two neutrino flavors (ν_e , ν_μ) 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. Let any neutrino state be represented as $|v\rangle = \psi_{1m}|\nu_{1m}\rangle + \psi_{2m}|\nu_{2m}\rangle$, then the evolution equations for neutrinos propagating through matter can be established in terms of (ν_{1m} , ν_{2m})⁹¹:

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

In the above equation, θ_m is the matter-effect mixing angle, and Δm_m^2 is the difference in the squares of the effective masses; their values are given by the following formula:

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

$$\frac{d\theta_m}{d\chi} = \frac{1}{2} \cdot \frac{\sin 2\theta_m}{\Delta m_m^2} \frac{dA_{CC}}{d\chi} \quad (4)$$

In equations (3) and (4), 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 $A_{CC} \equiv 2EV_{CC} = 2\sqrt{2}G_F N_e(\chi)$ (where G_F is the Fermi constant, $N_e(\chi)$ is the number density of electrons in matter, and V_{CC} is the effective potential). If the density of the propagation medium is constant, solving Equation (2) yields the conversion probabilities for the two neutrino flavors as:

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2 2\theta_m \sin^2 \left(\frac{\Delta m_m^2 L}{4E} \right) \quad (5)$$

Neutrinos enter resonance when the following condition is satisfied:

$$N_e = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F E} \quad (6)$$

At resonance, neutrinos achieve maximum mixing, and neutrino oscillations are significantly enhanced. This resonance was jointly discovered by Mikheyev, Smirnov, and Wolfenstein, and is therefore referred to as the MSW mechanism or MSW resonance.

After studying the MSW mechanism, Zhang and Zhang^{31-33,92} further pointed out that the MSW mechanism is actually a physical resonance between neutrinos and medium atoms, involving energy excitation that affects both the neutrinos and the medium nucleons. For neutrinos, this increases their mixing degree and the amplitude of their oscillations; for nucleons in the medium, it excites unstable radioactive nucleons into excited states, thereby increasing their decay probability (Fig. 5). Because atomic radioactivity is a tunneling effect⁹³ and a quantum transition phenomenon⁹⁴, it is highly sensitive to energy; even a negligible energy perturbation can cause the decay rate to increase exponentially. The Earth's interior is rich in radioactive materials. If neutrinos, while passing through the Earth, can form MSW resonance with the Earth's matter, then there is no doubt that this resonance would excite the Earth's radioactive materials, increasing their decay probability and generating more heat. Studies have shown that the energy spectrum of

atmospheric neutrinos ranges from 0.1 to 10^4 GeV, with peaks reaching the TeV level^{95,96}, and the density of Earth's matter ranges from 1 to 13 g/cm³⁹⁷. Based on the resonance conditions, all of Earth's matter is capable of forming MSW resonance with atmospheric neutrinos. In other words, radioactive materials in all layers of the Earth's interior can be excited by MSW resonance, accelerating their decay and generating heat.

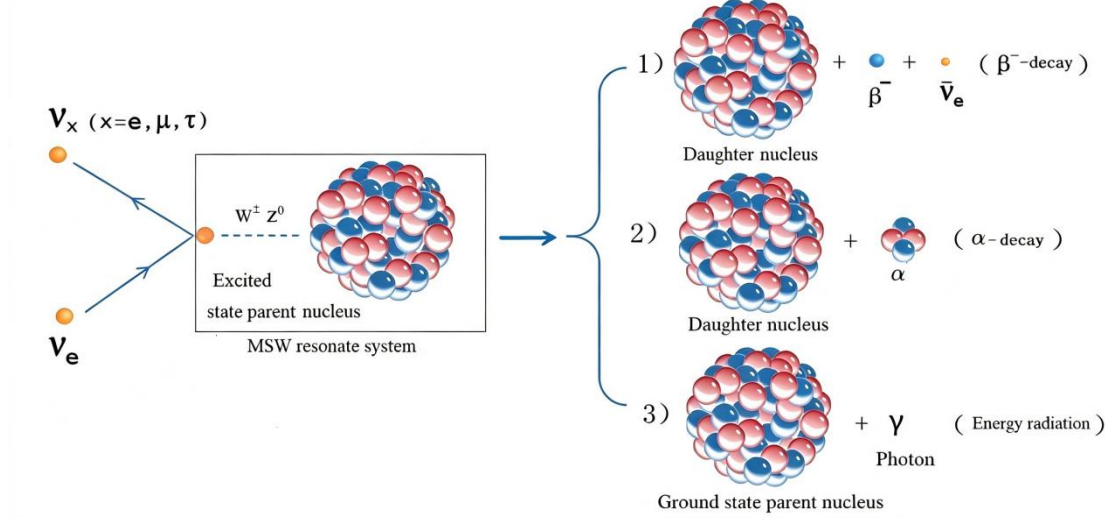


Fig. 5 Neutrino oscillations perturb radioactive nuclei to decay in an excited state. This image has been modified according to reference^{33,37}.

During resonance, the energy of atmospheric neutrinos can be expressed as^{31,33,98}:

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

In Equation (7), $\Delta m_{31}^2 = 2.49 \times 10^{-14} \text{eV}$, and $\sin^2 2\theta_{13} = 0.0875$. The relationship between N_e and the density of matter ρ is $N_e = Y_e \rho / m_N$, where Y_e is the electron-to-nucleon ratio (i.e., the number of electrons per nucleon), and m_N is the mass number of the nucleon.

The density of seawater is approximately 1g/cm³; the neutrino energy at which MSW resonance occurs in seawater is^{37,98}:

$$E_{\text{res}}^{\text{water}} \approx 31.5 \text{GeV} \left(\frac{1 \text{g/cm}^3}{\rho} \right) \left(\frac{\Delta m_{31}^2}{2.4 \times 10^{-3} \text{eV}^2} \right) \cos 2\theta_{13} \quad (8)$$

Two necessary conditions for MSW resonance

Atmospheric neutrinos propagate into the Earth's interior from the atmosphere, which is largely a vacuum. Owing to matter effects, neutrino oscillations are modified, leading to flavour transitions between ν_e and ν_μ , with the effective mixing angle changing from θ to θ_m . Since ν_e and ν_μ are superpositions of ν_{1m} and ν_{2m} , transitions also occur between ν_{1m} and ν_{2m} . When $\theta_m = \pi/4$ and the ν_{1m} and ν_{2m} states become degenerate, resonance develops (Fig. 6). This process requires a finite propagation time and a corresponding finite matter path length. As neutrinos travel at nearly the speed of light, even if this transition between ν_{1m} and ν_{2m} (i.e., the evolution of the mixing angle from θ to θ_m) completes within 10^{-5} seconds, the matter path length traversed reaches the kilometre scale. Zhang and Zhang³⁴ define the matter path length required for the mixing angle to evolve to θ_m and establish resonance as the initiation width of the MSW mechanism, denoted d_R (Fig. 6). If the matter thickness is less than d_R , resonance

cannot develop even when neutrino energy and medium density satisfy standard resonance conditions. Accordingly, two necessary conditions for MSW resonance formation in matter can be formulated: 1) The neutrino energy and medium density satisfy the fundamental resonance condition; 2) The thickness of the matter layer exceeds d_R . Once resonance is established, it can alter radioactive nucleon decay processes; hence, d_R also corresponds to the minimum matter width at which resonance can affect radioactive nucleon decay. Further calculations by Zhang³⁷ estimate d_R to be 1500 m.

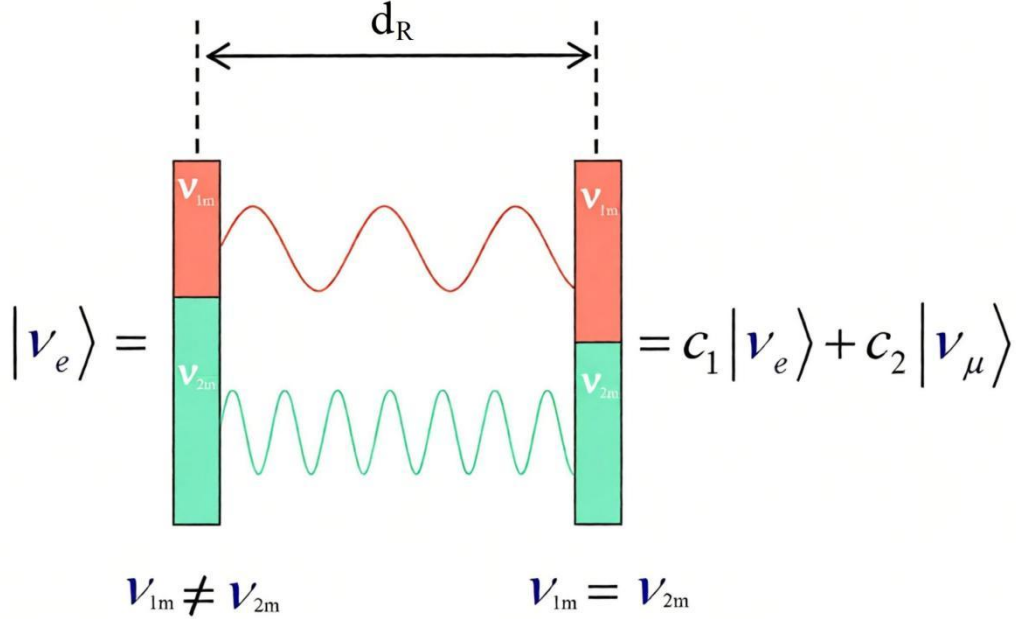
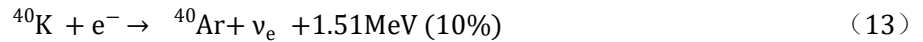
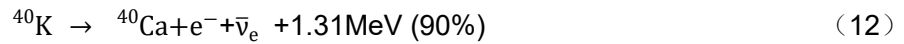
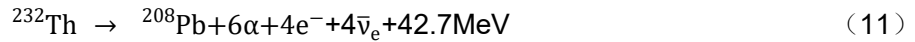
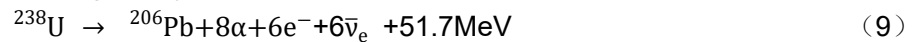


Fig. 6 The initiation width d_R formed by the MSW resonance of neutrino oscillations³⁷.

Magma formation

The four major radioactive isotopes in the Earth's interior— ^{238}U , ^{235}U , ^{232}Th , and ^{40}K —undergo the following decay reactions under the influence of neutrino oscillations⁶⁸:



Calculations show³¹ that if MSW resonance can trigger the decay of 3.02% of the major radioactive isotopes in the upper mantle, this would be sufficient to cause melting of the upper mantle. In the lower mantle and the core, due to the scarcity of radioactive materials⁹⁹, the heat generated by radioactive decay induced by atmospheric neutrino oscillation perturbations is insufficient to cause melting, making it difficult for a melt to form³¹. Although the Earth's crust is rich in radioactive materials, due to complex variations in crustal density, there are virtually no rock layers wider than 1,500 m with constant density, which fails to meet the conditions for MSW resonance formation. Therefore, radioactive materials in the crust will not be resonantly excited and will not produce melt^{31,33}. Consequently, Zhang and Zhang^{31–33} argue that magma within the Earth's interior primarily originates from the upper mantle and the asthenosphere.

Melting induced by neutrino oscillation perturbations first occurs in tiny regions enriched with radioactive materials, forming melt pockets of various shapes^{31,58}. These tiny melt pockets are typically distributed randomly throughout the upper mantle and are not interconnected; they serve as the embryos of magma. As MSW resonance continues to cause perturbations, radioactive heat generation increases, the melted regions gradually expand, and the melt pockets gradually transform into larger droplets, merging with surrounding melt pockets and droplets to form a flowable melt. Driven by buoyancy, these melts rise; upon reaching the lithosphere, their migration is further influenced by tectonic stresses. Since the upper mantle is plastic, melts ascend through it primarily by permeation. Upon reaching the rigid crust, because mineral crystals are resistant to creep, the melt cannot continue to rise by permeation and can only migrate along faults and fractures toward regions of lower stress, thereby driving various tectonic movements on Earth^{31–33,37}.

References

1. Glass, B. P. Tektites and microtektites: key facts and inferences. *Tectonophysics* **171**, 393-404 (1990). [https://doi.org/10.1016/0040-1951\(90\)90112-L](https://doi.org/10.1016/0040-1951(90)90112-L)
2. Li, C. L. Ooyang, Z. Y. Research progress of (micro)tektites. *Chin. Sci. Bull.* **42**, 1681-1695(1997). <https://doi.org/10.1360/csb1997-42-16-1681>
3. Pan, Q. et al. Magnetic Properties of Australasian Tektites From South China. *Journal of Geophysical Research: Solid Earth* **128**, e2022JB025269(2023). <https://doi.org/10.1029/2022JB025269>
4. Rochette, P. et al. Impact glasses from Belize represent tektites from the Pleistocene Pantasma impact crater in Nicaragua. *Commun Earth Environ* **2**, 94 (2021). <https://doi.org/10.1038/s43247-021-00155-1>
5. Di Vincenzo, G., Folco, L., Suttle, M. D., Brase, L. & Harvey, R. P. Multi-collector ⁴⁰Ar/³⁹Ar dating of microtektites from Transantarctic Mountains (Antarctica): A definitive link with the Australasian tektite/microtektite strewn field. *Geochimica et Cosmochimica Acta*. **298**, 112-130(2021). <https://doi.org/10.1016/j.gca.2021.01.046>
6. Soens, B. et al. Australasian microtektites across the Antarctic continent: Evidence from the Sor Rondane Mountain range (East Antarctica). *Geoscience Frontiers* **12**, 101153(2021). <https://doi.org/10.1016/j.gsf.2021.101153>
7. Beran, A., Koeberl, C. Water in tektites and impact glasses by Fourier-Transformed Infrared Spectrometry. *Meteoritics Planet. Sci.* **32**, 211-216(1997). <https://doi.org/10.1111/j.1945-5100.1997.tb01260.x>
8. Pasek, M. A., Block, K. & Pasek, V. Fulgurite morphology: a classification scheme and clues to formation. *Contrib Mineral Petrol* **164**, 477–492 (2012). <https://doi.org/10.1007/s00410-012-0753-5>
9. Koeberl, C. Tektite Origin by Hypervelocity Asteroidal or Cometary Impact: Target Rocks, Source Craters, and Mechanisms. *Geological Society of America Special Paper* **293**, 133-152 (1992). <http://dx.doi.org/10.1130/SPE293-p133>
10. Wasson, J. T. Large aerial bursts: an important class of terrestrial accretionary events *Astrobiology* **3**, 163-179(2003). <https://doi.org/10.1089/153110703321632499>

11. O'Keefe, J. A. The Tektite Problem. *Scientific American* **239**, 116–127(1978).
<https://doi.org/10.1038/scientificamerican0878-116>
12. Adams, E. W., Huffaker, R. M. Aerodynamic analysis of the tektite problem. *Geochimica et Cosmochimica Acta* **28**, 881-892(1964).
[https://doi.org/10.1016/0016-7037\(64\)90037-7](https://doi.org/10.1016/0016-7037(64)90037-7)
13. Chapman, D. R. and Larson, H. K. On the lunar origin of tektites. *J. Geophys. Res.* **68**, 4305–4358(1963). <https://doi.org/10.1029/JZ068i014p04305>
14. Chalmers, R. O., Henderson, E. P., Mason, B. Occurrence, Distribution, and Age of Australian Tektites. *Smithsonian Contributions to the Earth Sciences*, Smithsonian Institution Press. Washington (1976). <https://doi.org/10.5479/si.00810274.17.1>
15. Schmieder, M., Kring, D. A. Earth's Impact Events Through Geologic Time: A List of Recommended Ages for Terrestrial Impact Structures and Deposits. *Astrobiology* **20**, 91-141(2020). <https://doi.org/10.1089/ast.2019.2085>
16. Keller, G., D'Hondt, S. L. & Vallier, T. L. Multiple Microtektite Horizons in Upper Eocene Marine Sediments: No Evidence for Mass Extinctions. *Science* **221**, 150-152(1983). <https://doi.org/10.1126/science.221.4606.150>
17. Lin, W. Z. & Ouyang, Z. Y. Classes after nuclear explosion and from impact craters and source rocks of tektite. *Chinese Journal of Geology* **26**, 148-158(1991).
18. Li, C. L., Ouyang, Z. Y., Liu, T. & An, Z. S. Microteklites and glassy microtektites in loess: Their discovery and implications, *Science in China, Ser. B* **36**, 1141(1993).
<https://doi.org/10.1360/zb1992-22-11-1210>
19. Gattacceca, J., Rochette, P., Quesnel, Y. & Singsoupho, S. Revisiting the paleomagnetism of Muong Nong layered tektites: Implications for their formation process. *Meteoritics & Planetary Sciences* **57**, 558–571(2022).
<https://doi.org/10.1111/maps.13703>
20. de Gasparis, A. A., Fuller, M., Cassidy, W. Natural Remanent Magnetism of Tektites of the Muong-Nong Type and Its Bearing on Models of Their Origin. *Geology* **3**, 605-607(1975). [https://doi.org/10.1130/0091-7613\(1975\)3<605:NRMOTO>2.0.CO;2](https://doi.org/10.1130/0091-7613(1975)3<605:NRMOTO>2.0.CO;2)
21. Storzer, D. & Wagner, G. A. Australites older than indochinites. *Naturwissenschaften* **67**, 90–91 (1980). <https://doi.org/10.1007/BF01054692>
22. Fleischer, R. L., Price, P. B., Woods, R. T. A second tektite fall in Australia. *Earth Planet Sci. Lett.* **7**, 51-52 (1969). [https://doi.org/10.1016/0012-821X\(69\)90011-9](https://doi.org/10.1016/0012-821X(69)90011-9)
23. Westgate, J. A., Pillans, B. J., Alloway, B. V., Pearce, N. J.G., Simmonds, P. New fission-track ages of Australasian tektites define two age groups: discriminating between formation and reset ages. *Quaternary Geochronology* **66**, 101113(2021).
<https://doi.org/10.1016/j.quageo.2020.101113>
24. Lovering, J. F., Mason, B., Williams, G. E. & Mccoll, D. Stratigraphical evidence for the terrestrial age of australites. *J Geol Soc Aust.* **18**, 409–418(1972).
<https://doi.org/10.1080/00167617208728779>
25. Glass, B. P. Australasian microtektites and the stratigraphic age of the australites. *Geol Soc Am Bull.* **89**, 1455-1458(1978)
[https://doi.org/10.1130/0016-7606\(1979\)90<510:amatsa>2.0.co;2](https://doi.org/10.1130/0016-7606(1979)90<510:amatsa>2.0.co;2)
26. Hazel, J. E. Chronostratigraphy of upper Eocene microspherules. *Palaios* **4**, 318–329(1989). <https://doi.org/10.2307/3514556>

27. Glass, B. P. Reworking of deep-sea sediments as indicated by the vertical dispersion of the Australasian and Ivory Coast microtektite Horizons. *Earth Planet. Sci. Lett.* **6**, 409-415(1969). [https://doi.org/10.1016/0012-821X\(69\)90109-5](https://doi.org/10.1016/0012-821X(69)90109-5)
28. Rudraswami, N. G. et al. Geochemistry of aerodynamically distorted Australasian microtektites: Implications for ejecta on Mars and Venus. *J. Earth Syst. Sci.* **130**, 1–21(2021). <https://doi.org/10.1007/s12040-021-01589-z>
29. Futrell, D. Implication of welded breccia in Muong Nong-type tektites. *Nature* **319**, 663–665 (1986). <https://doi.org/10.1038/319663a0>
30. Glass, B. P., Folco, L., Masotta, M. and Campanale, F. Coesite in a Muong Nong-type tektite from Muong Phin, Laos: Description, formation, and survival. *Meteorit Planet Sci.* **55**, 253-273 (2020). <https://doi.org/10.1111/maps.13433>
31. Zhang, G. W. & Zhang, M. K. Effects of Matter in Atmospheric Neutrino Oscillations and the Formation of Magma. *Journal of Geoscience and Environment Protection* **12**, 270-287 (2024). <https://doi.org/10.4236/gep.2024.1212017>
32. Zhang, M. & Zhang, G. Dynamical Mechanisms of Melt Migration Beneath Mid-Ocean Ridges. *Open Journal of Geology* **15**, 358-376(2025). <https://doi.org/10.4236/ojg.2025.157018>
33. Zhang, M. K. & Zhang, G. W. The Formation of Mantle Melt and the Causes of Its Heterogeneous Distribution. *Journal of Geoscience and Environment Protection* **14**, 23-40(2026). <https://doi.org/10.4236/gep.2026.146002>
34. Wolfenstein, L. Neutrino Oscillations in Matter. *Physical Review D* **17**, 2369-2379(1978). <https://doi.org/10.1103/PhysRevD.17.2369>
35. Mikheyev, S. P. & Smirnov, A Y. Resonant amplification of neutrino oscillations in matter and solar neutrino spectroscopy. *Nuovo Cim. C* **9**, 17-26(1986) . <https://doi.org/10.1007/BF02508049>
36. Mikheyev, S. P. & Smirnov, A .Y. Resonant Neutrino Oscillations in Matter. *Progress in Particle and Nuclear Physics* **23**, 41-136(1989). [https://doi.org/10.1016/0146-6410\(89\)90008-2](https://doi.org/10.1016/0146-6410(89)90008-2)
37. Zhang, G. W. Magma Generation in the ocean continental transition of the Northern South China Sea Continental Margin and Its Modification of the Crust. *Research Square*, July 15(2026). <https://doi.org/10.21203/rs.3.rs-10350774/v1>
38. Cohen, A. Trace Element Relationships and Terrestrial Origin of Tektites. *Nature* **188**, 653–654 (1960). <https://doi.org/10.1038/188653a0>
39. Koeberl, C. The geochemistry of tektites: an overview. *Tectonophysics* **171**, 405-422(1990). [https://doi.org/10.1016/0040-1951\(90\)90113-M](https://doi.org/10.1016/0040-1951(90)90113-M)
40. Zhang, L., Liu, J. Z., Zhao, H. Q. & Li, C. L. Physical properties, major element composition and complexity of parent material of microtektites from ODP core 1144 in the South China Sea. *Geology Geochemistry* **31**, 65-72(2003).
41. Haskin, L., Gehl, M. A. Rare-Earth Elements in Tektites. *Science* **139**, 1056-1058 (1963). <https://doi.org/10.1126/science.139.3559.1056>
42. Bouřka, V. Řanda, Z. Rare earth elements in tektites. *Geochimica et Cosmochimica Acta* **40**, 486-488(1976). [https://doi.org/10.1016/0016-7037\(76\)90016-8](https://doi.org/10.1016/0016-7037(76)90016-8)
43. Glass, B. P. Zircon and Chromite Crystals in a Muong Nong-Type Tektite. *Science* **169**, 766-769 (1970). <https://doi.org/10.1126/science.169.3947.766>

44. Glass, B. P. Crystalline inclusions in a Muong Nong-type indochinite. *Earth and Planetary Science Letters* **16**, 23-26(1972).
[https://doi.org/10.1016/0012-821X\(72\)90232-4](https://doi.org/10.1016/0012-821X(72)90232-4)
45. Kinnunen, K. A. Lechatelierite inclusions in indochinites and the origin of tektites. *Meteoritics* **25**,181-184(1990). <https://doi.org/10.1111/j.1945-5100.1990.tb00994.x>
46. Zanetta, P. M., Rochette, P., Seydoux-Guillaume, A. M., Andrieu, V. and Guilbaud, C. Organic residues from biomass in a Muong Nong Australasian tektite. *Meteorit Planet Sci.* **61**, 664-678(2026). <https://doi.org/10.1111/maps.70116>
47. Liao, J.L. et al. Quantifying the controlling mineral phases of rare-earth elements in deep-sea pelagic sediment. *Chemical Geology* **595**,120792(2022).
<https://doi.org/10.1016/j.chemgeo.2022.120792>
48. Koeberl, C. Geochemistry and origin of Muong Nong-type tektites. *Geochimica et Cosmochimica Acta.* **56**,1033–1064(1992).
[https://doi.org/10.1016/0016-7037\(92\)90046-L](https://doi.org/10.1016/0016-7037(92)90046-L)
49. Zanetta, P. M. et al. Origin of the Ca-phosphate inclusions in Ivory Coast and Australasian Muong-Nong-type tektites. *Geochimica et Cosmochimica Acta.* **387**, 63-82(2024) <https://doi.org/10.1016/j.gca.2024.09.021>
50. Musolino, A. et al. A new tektite strewn field in Australia ejected from a volcanic arc impact crater 11 Myr ago. *Earth and Planetary Science Letters* **670**,119600(2025).
<https://doi.org/10.1016/j.epsl.2025.119600>
51. Wilding, M., Webb, S., Dingwell, D. B. Tektite cooling rates: Calorimetric relaxation geospeedometry applied to a natural glass. *Geochimica et Cosmochimica Acta*, **60**, 1099-1103(1996). [https://doi.org/10.1016/0016-7037\(96\)00010-5](https://doi.org/10.1016/0016-7037(96)00010-5)
52. Li, T. The statistical characteristics of the abundance of chemical elements in the Earth's Crust. *Geology and Prospecting* **28**, 1-7(1992).
53. Zhu, L.M., Gao, Z.Y., Yin, G., Xu, J. Content and spatial change of rare earth element and trace element of surficial sediment in the South China Sea. *Acta Petrologica Sinica* **23**, 2963-2980(2007).
54. Dong, H. K. et al. Mineralogical and geochemical constraints on the origin of rhythmic layering of Late Miocene reddish-brown and greenish-gray sediments in the northern South China Sea. *Earth Science Frontiers* **29**, 42-54(2022).
<https://doi.org/10.13745/j.esf.sf.2022.1.11>
55. El-Taher, A., Badawy, W. M., Khater, A.E.M., Madkour, H.A. Distribution patterns of natural radionuclides and rare earth elements in marine sediments from the Red Sea, Egypt. *Applied Radiation and Isotopes* **151**,171-181(2019).
<https://doi.org/10.1016/j.apradiso.2019.06.001>
56. Ouyang, Z. Y., Zhong, P. H. & Yi, W. X. Trace Element in Tektite from Hainan Island, China. *Geochimica* **2**, 144-147(1976).
<https://doi.org/10.19700/j.0379-1726.1976.02.008>
57. Wen, H., Lu, J. H., Xiao, Y., Deng, J. Temperature dependence of thermal conductivity, diffusion and specific heat capacity for coal and rocks from coalfield. *Thermochimica Acta* **619**, 41-47(2015). <https://doi.org/10.1016/j.tca.2015.09.018>

58. Chazot, G., Menzies, M., Harte, B. Silicate glasses in spinel lherzolites from Yemen: origin and chemical composition. *Chem Geol.* **134**,159–179(1996) .
[https://doi.org/10.1016/S0009-2541\(96\)00086-1](https://doi.org/10.1016/S0009-2541(96)00086-1)
59. Alexey, N. et al. Potassium-rich granite melt inclusions in zircon from gabbro-hosted felsic stringers, Mid-Atlantic Ridge at 13°34'N: E-MORB connection. *Lithos* **400–401**, 106300(2021). <https://doi.org/10.1016/j.lithos.2021.106300>
60. Ferrière, L. et al. Distinguishing volcanic from impact glasses – The case of the Cali glass (Colombia). *Geology* **49**, 1421–1425(2021). <https://doi.org/10.1130/G48925.1>
61. Giuli, G. et al. Iron redox variations in Australasian Muong Nong-type tektites. *Meteorit Planet Sci.* **61**,1179-1187(2026). <https://doi.org/10.1111/maps.70156>
62. Mizote, S., Matsumoto, T., Matsuda, J., Koeberl, C. Noble gases in muong nong type tektites and their implications. *Meteoritics & Planetary Science* **38**, 747-758(2003).
<https://doi.org/10.1111/j.1945-5100.2003.tb00039.x>
63. Fiske, P. S. et al. Layered Tektites of Southeast Asia: Field Studies in Central Laos and Vietnam. *Meteoritics & Planetary Science* **34**, 757-761(1999).
<https://doi.org/10.1111/j.1945-5100.1999.tb01388.x>
64. Campanale, F. et al. Evidence for subsolidus quartz-coesite transformation in impact ejecta from the Australasian tektite strewn field. *Geochimica et Cosmochimica Acta* **264**,105-117(2019). <https://doi.org/10.1016/j.gca.2019.08.014>
65. Masotta, M. et al. 3D X-ray tomographic analysis reveals how coesite is preserved in Muong Nong-type tektites. *Sci Rep.* **10**, 20608 (2020).
<https://doi.org/10.1038/s41598-020-76727-6>
66. Campanale, F., Mugnaioli, E., Gemmi, M., Folco, L. The formation of impact coesite. *Sci Rep.* **11**, 16011 (2021). <https://doi.org/10.1038/s41598-021-95432-6>
67. Yatsevich, I., Honda, M. Production of nucleogenic neon in the Earth from natural radioactive decay. *J. Geophys. Res.* **102(B5)**, 10291–10298(1997).
<https://doi.org/10.1029/97JB00395>
68. Dye, S. T. Geoneutrinos and the radioactive power of the Earth. *Reviews of Geophysics* **50**, RG3007(2012). <https://doi.org/10.1029/2012RG000400>
69. Tada, T. et al. In situ occurrence of Muong Nong-type Australasian tektite fragments from the Quaternary deposits near Huai Om, northeastern Thailand. *Progress Earth Planet. Sci.* **7**, 66(2020). <https://doi.org/10.1186/s40645-020-00378-4>
70. Zhang Y., Walker D., and Leshner C. E. Diffusive crystal dissolution. *Contributions to Mineralogy and Petrology* **102**, 492–513(1989). <https://doi.org/10.1007/BF00371090>
71. Wang, W., Mo, J. & Huang, Z. Recent discovery of handaxes associated with tektites in the Nanbanshan locality of the Damei site, Bose basin, Guangxi, South China. *Chin. Sci. Bull.* **53**, 878–883 (2008). <https://doi.org/10.1007/s11434-008-0134-7>
72. Guo, Y. H., Chen, H., Li, D. W., Xie, G. M. & Xue, L. P. Research on the tektite artifacts unearthed at the Yahuai Cave site in Guangxi. *Acta Anthropologica Sinica* **44**, 451-465(2025). <https://doi.org/10.16359/j.1000-3193/AAS.2025.0049>
73. Glass, B.P., Baker, R. N., Storzer, D., Wagner, G. A. North American microtektites from the Caribbean Sea and their fission track age. *Earth and Planetary Science Letters* **19**, 184-192(1973). [https://doi.org/10.1016/0012-821X\(73\)90113-1](https://doi.org/10.1016/0012-821X(73)90113-1)

74. Sigurdsson, H. et al. Glass from the Cretaceous/Tertiary boundary in Haiti. *Nature* **349**, 482–487 (1991). <https://doi.org/10.1038/349482a0>
75. Glass, B. Microtektites in Deep-sea Sediments. *Nature* **214**, 372–374 (1967). <https://doi.org/10.1038/214372b0>
76. Peng, H. C., Yu, Z. & Zhuang, S. J. Preliminary study of microtektites first discovered in the central Pacific by China. *Acta Oceanologica Sinica* **5**, 1-8(1983).
77. Wang, J. L., Zhao, Q. H., Cheng, X. R., Wang, R. J. & Wang, P. X. Age estimation of the mid-Pleistocene microtektite event in the South China Sea: A case showing the complexity of the sea-land correlation. *Chin. Sci. Bull.* **45**, 2277-2280(2000). <https://doi.org/10.1007/BF02886368>
78. Schneide, D. A., Kent, D. V. & MelloG, A. A. detailed chronology of the Australasian impact event, the Brunhes-Matuyama geomagnetic polarity reversal, and global climatic change. *Earth Planet Sci. Lett.* **111**, 395-405(1992). [https://doi.org/10.1016/0012-821X\(92\)90192-X](https://doi.org/10.1016/0012-821X(92)90192-X)
79. Zhu, Z. Y., Zhou, H. Y., Qiao, Y. L., Zhang, H. X. & Liang, J. P. Initial Strata Occurrence of the South China Tektite in Strata and Its Implication for Event-Stratigraphy. *Journal of Geomechanics* **7**, 296-302(2001).
80. Yin, Y. H., Wan, T. F. & Sun, J. S. The microtektites in hole B at site 573 of DSDP in the East Pacific. *Marine Geology & Quaternary Geology* **21**, 37-42(2001). <https://doi.org/10.16562/j.cnki.0256-1492.2001.04.007>
81. Li, W. B., Wang, R. J. & Ding, X. H. Microtektites in deep-sea sediments of the southern tasman sea: the environmental effect recorded in the extraterrestrial impact event. *Quaternary Sciences* **31**, 849-855(2011).
82. Glass, B.P. and Koeberl, C. Australasian microtektites and associated impact ejecta in the South China Sea and the Middle Pleistocene supereruption of Toba. *Meteoritics & Planetary Science*, **41**, 305-326(2006). <https://doi.org/10.1111/j.1945-5100.2006.tb00211.x>
83. Zhao, Q., Jian, Z., Li, B., Cheng, X. R. & Wang, P. X. Microtektites in the Middle Pleistocene deep-sea sediments of the South China Sea*. *Sci. China Ser. D-Earth Sci.* **42**, 531–535 (1999). <https://doi.org/10.1007/BF02875247>
84. Jourdan, F., Renne, P. R. & Reimold, W. U. The problem of inherited $^{40}\text{Ar}^*$ in dating impact glass by the $^{40}\text{Ar}/^{39}\text{Ar}$ method: Evidence from the Tswaing impact crater (South Africa). *Geochimica et Cosmochimica Acta* **71**, 1214-1231(2007). <https://doi.org/10.1016/j.gca.2006.11.013>
85. Schwarz, W. H. and Lippolt, H. J. ^{40}Ar - ^{39}Ar step-heating of impact glasses from the Nördlinger Ries impact crater—Implications on excess argon in impact melts and tektites. *Meteorit Planet Sci.* **49**, 1023-1036 (2014). <https://doi.org/10.1111/maps.12309>
86. Magna, T. et al. Potassium elemental and isotope constraints on the formation of tektites and element loss during impacts. *Geochimica et Cosmochimica Acta* **312**, 321-342(2021). <https://doi.org/10.1016/j.gca.2021.07.022>
87. Deng, X. et al. The behavior of rubidium during evaporation: evidence from element and isotope compositions of tektites. *Geochimica et Cosmochimica Acta* **428**, 1-12(2026). <https://doi.org/10.1016/j.gca.2026.07.022>

88. Ackerman, L. et al. Magna Sr-Nd-Pb isotope systematics of Australasian tektites: implications for the nature and composition of target materials and possible volatile loss of Pb *Geochim. Cosmochim. Acta* **276**, 135-150(2020).
<https://doi.org/10.1016/j.gca.2020.02.025>
89. Creech, J.B., Moynier, F., Koeberl, C. Volatile loss under a diffusion-limited regime in tektites: Evidence from tin stable isotopes *Chem. Geol.* **528**, 119279 (2019).
<https://doi.org/10.1016/j.chemgeo.2019.119279>
90. Jiang, Y. et al. Implications of K, Cu and Zn isotopes for the formation of tektites *Geochim. Cosmochim. Acta* **259**, 170-187(2019).
<https://doi.org/10.1016/j.gca.2019.06.003>
91. de Holanda, P. C., Liao, W. & Smirnov, A. Y. Toward precision measurements in solar neutrinos. *Nucl. Phys. B* **702**, 307-332(2004).
<https://doi.org/10.1016/j.nuclphysb.2004.09.027>
92. Zhang, G. W. & Zhang, M. K. Research on Neutrino Oscillation-Induced Radioactive Decay. *Modern Physics* **14**, 135-144(2024).
<https://doi.org/10.12677/mp.2024.144016>
93. Gurney, R. W. & Condon, E. U. Quantum Mechanics and Radioactive Disintegration . In: Barut A O, Odabasi H, van der Merwe, A. (eds) *Selected Scientific Papers of E.U. Condon*. Springer, New York, NY (1991).
https://doi.org/10.1007/978-1-4613-9083-1_11
94. Fermi, E. Versuch einer Theorie der β -Strahlen. I. *Zeitschrift für Physik* **88**, 161-177(1934). <https://doi.org/10.1007/BF01351864>
95. Honda, M., Kajita, T., Kasahara, K. & Midorikawa, S. Calculation of the Flux of Atmospheric Neutrinos. *Physical Review D* **52**, 4985-5005 (1995).
<https://doi.org/10.1103/physrevd.52.4985>
96. Gaisser, T. K. & Honda, M. Flux of Atmospheric Neutrinos. *Annual Review of Nuclear and Particle Science* **52**, 153-199(2002).
<https://doi.org/10.1146/annurev.nucl.52.050102.090645>
97. Dziewonski, A. M. & Anderson, D. L. Preliminary reference Earth model. *Phys. Earth Planet. Inter.* **25**, 297-356(1981). [https://doi.org/10.1016/0031-9201\(81\)90046-7](https://doi.org/10.1016/0031-9201(81)90046-7)
98. Upadhyay, A. K., Kumar, A., Agarwalla, S. K. & Dighe, A. Locating the core-mantle boundary using oscillations of atmospheric neutrinos. *J. High Energ. Phys.* **2023**, 68 (2023). [https://doi.org/10.1007/JHEP04\(2023\)068](https://doi.org/10.1007/JHEP04(2023)068)
99. Li, T. Chemical Element Abundances in the Earth and Its Major Shells. *Geochimica* **5**, 167-174 (1976). <https://doi.org/10.19700/j.0379-1726.1976.03.001>

Data availability

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

Code availability

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