

Phantom recycled carbonates and mantle pyroxenites: insight from the low- $\delta^{26}\text{Mg}$ intraplate basaltic province across central-eastern Asia

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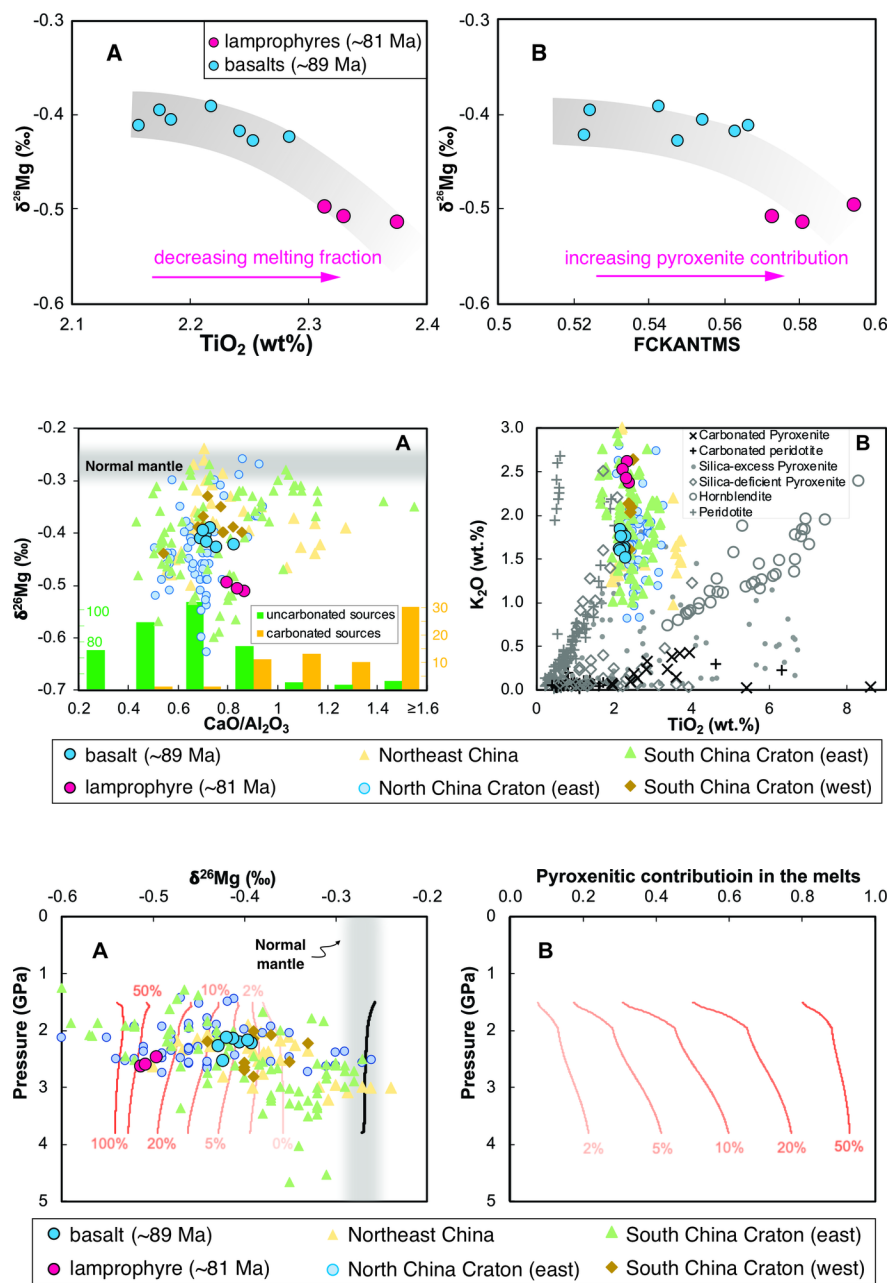
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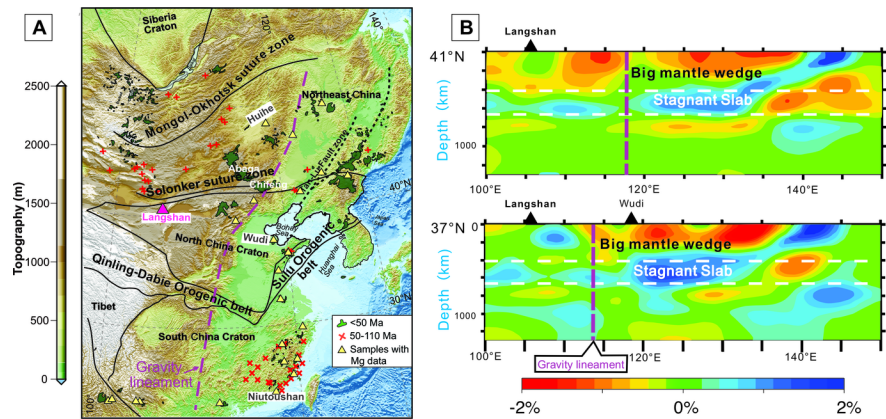
Abstract

Mass recycling from subduction to magmatic extrusion shapes our habitable environment and Earth's interior. Subducted igneous crust may form pyroxenites before participating magmatism, but the deep journey of associated carbonates remains unclear. Here we report new Mg-isotope data for ~89 to 81 Ma basaltic rocks in Langshan area, central Asia ($\delta^{26}\text{Mg} = -0.391$ to -0.513 ‰) for post-110 Ma basalts across eastern Asian continent. The merged low- $\delta^{26}\text{Mg}$ basaltic province normally interpreted as derivations from carbonated sources paradoxically displays geochemical signatures (low Ca/Al and high K_2O contents) resembling partial melts of uncarbonated sources. Negative correlations of $\delta^{26}\text{Mg}$ vs TiO_2 and FCKANTMS, the proxy of pyroxenitic melts, and adiabatic melting modeling suggest presence of Mg-isotopically light source pyroxenites transformed from decarbonated altered oceanic crust. This may explain ubiquitous pyroxenitic contributions in many low- $\delta^{26}\text{Mg}$ basaltic suites and has significant implication for deep carbon cycling.

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Phantom recycled carbonates and mantle pyroxenites: insight from the low- ^{26}Mg intraplate basaltic province across central-eastern Asia

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Key Points:

- The Langshan basaltic rocks and the post-110 Ma eastern Asian equivalents paradoxically have low ^{26}Mg but low Ca/Al and high K₂O contents
- The paradox suggests transformation of low- ^{26}Mg mantle pyroxenites from decarbonated altered oceanic crust before the magmatism
- Decarbonation-related pyroxenite is pervasive in sources of intracontinental basaltic provinces and has implication for deep carbon cycling

Abstract

Mass recycling from subduction to magmatic extrusion shapes our habitable environment and Earth's interior. Subducted igneous crust may form pyroxenites before participating magmatism, but the deep journey of associated carbonates remains unclear. Here we report new Mg-isotope data for ~89 to 81 Ma basaltic rocks in Langshan area, central Asia ($^{26}\text{Mg} = -0.391$ to -0.513 ‰) with a synthesis for post-110 Ma basalts across eastern Asian continent. The merged low- ^{26}Mg basaltic province normally interpreted as derivations from carbonated sources paradoxically displays geochemical signatures (low Ca/Al and high K₂O contents) resembling partial melts of uncarbonated sources. Negative correlations of ^{26}Mg vs TiO₂ and FCKANTMS, the proxy of pyroxenitic melts, and adiabatic melting modeling suggest presence of Mg-isotopically light source pyroxenites transformed from decarbonated altered oceanic crust. This may explain ubiquitous pyroxenitic contributions in many low- ^{26}Mg basaltic suites and has significant implication for deep carbon cycling.

Plain Language Summary

Oceanic slab subduction and returning to the surface via magmatism exerts important control on our habitable environment and Earth's interior. However,

the deep journey of different subducted components (e.g., igneous crust, carbonates, etc.) is understood unevenly. Subducted igneous crust usually forms mantle pyroxenites before involvement in basaltic generation, but it is unclear if associated carbonates are directly involved or undergo other steps. Here, we explore this puzzle by integrating new Mg-isotope data for Late Cretaceous basaltic rocks in central Asia ($^{26}\text{Mg} = -0.391$ to -0.513 ‰) with a synthesis for post-110 Ma intraplate basalts across eastern Asia. The merged low- ^{26}Mg magmatic province traditionally interpreted as derivations from carbonated sources paradoxically shows element evidence (low Ca/Al and high K_2O contents) for uncarbonated sources. Negative correlations of ^{26}Mg values with TiO_2 contents and the proxy of pyroxenite contribution and adiabatic melting modeling further suggest presence of Mg-isotopically light pyroxenites in the magma sources that may be transformed from decarbonated altered oceanic crust. This may represent a ubiquitous mechanism for pyroxenitic contributions in many geochemically similar intracontinental small-volume basalts and has important implication for global deep carbon cycling.

1 Introduction

Oceanic slab subduction and returning to the surface shapes our habitable environment and Earth’s interior. Intracontinental basaltic magmatism, commonly occurring as widely dispersed monogenetic basaltic activities (McGee and Smith, 2016), is an important outflux of subducted materials (Foley and Fisher, 2017). However, the deep journey of different subducted components (e.g., igneous crust, carbonates, etc.) is understood unevenly. The residual igneous crust after extraction of fusible components (e.g., silica, volatiles, etc.) in the shallow subduction processes (Stracke et al., 2003) is generally considered to form pyroxenites (and eclogites) before participating basaltic magmatism (e.g., Kogiso et al., 2003). Proposed mechanisms for the pyroxenite formation include (1) metamorphic transformation of the residual crust, (2) reaction between the transformed pyroxenite (or its partial melts) and ambient peridotite, and 3) the cumulates caused by the commingling between pyroxenitic and peridotitic partial melts (Herzberg, 2011). In contrast, it is still controversial if the subducted carbonates, including the sedimentary carbonates and those precipitated in the altered oceanic crust, are directly involved in, or undergo other steps before the magmatism (Li et al., 2017; Wang et al., 2018).

Direct carbonate involvement, especially in the intraplate alkaline basaltic extrusions, has been proposed to interpret the distinct metal stable isotopic compositions (e.g., light Mg, heavy Zn) of these extrusions (e.g., Li et al., 2017; Liu et al., 2022). The philosophy behind includes the possible carbonate survival from subduction processes into the asthenosphere or even deeper (Kelemen and Manning, 2015), the canonical stable metal isotope signatures (e.g., Teng et al., 2017), and the negligible isotope fractionation during the high-temperature mantle processes that enable the propagation of the isotope signatures from recycled carbonates to their derivatives (Liu and Li, 2019). Alternatively, extensive

studies using elemental and radiogenic isotopic systematics suggest that alkaline basaltic extrusions may represent low-degree partial melts of mantle domains containing non-peridotite lithologies (Hauri, 1996; Herzberg et al., 2014). Thus, it seems the Jainist concept of Anekantavada, where the stable metal isotopic protocols and the traditional element-isotopic systematics tap different aspects of the melt sources.

The post-110 Ma dispersed basaltic eruptions across the central-eastern Asia (Fig. 1A) constitute a typical “diffuse” intercontinental basaltic province. They have highly similar geochemical signatures (Fig. S1), including low silica and high alkali-element contents, oceanic island basalt (OIB)-like trace-element patterns and moderately depleted Sr-Nd isotope compositions (Sheldrick et al., 2020). Their mantle sources are now considered to be pyroxenite-bearing asthenospheric domains polluted by recycled slab materials from multiple subduction episodes that contributed to the construction of the vast central-eastern Asian landmass (Xu et al., 2018; Dai et al., 2021a). In particular, the basaltic rocks east of the N-S gravity lineament cutting the North China Craton (directly above the stagnant (Paleo-) Pacific slab, Fig. 1B) commonly have light Mg-isotope compositions ($^{26}\text{Mg} = -0.24$ to -0.63 ‰ with an average of -0.41 ‰); they are considered as evidence for a huge, recycled carbon reservoir in the upper mantle (e.g., Li et al., 2017) that is genetically linked to the subducted (Paleo-) Pacific slab based on their spatial and temporal affinity and the light Mg isotopes canonical to sedimentary carbonates (Teng et al., 2017). Due to the scarcity of Mg-isotope data for basalts west of the gravity lineament, it is not yet clear if such isotopic signatures and the inferred subduction-related carbon reservoir can be extended to the region beyond the influence of the present-day stagnant Pacific slab (Fig. 1B). Moreover, the genetic link between the recycled carbonates and pyroxenites in the sources of these basaltic rocks remains unclear.

In this study, new Mg-isotope data (Supplementary Table S1) on Late Cretaceous basaltic rocks from the Langshan area, central Asia (outside the influence of the stagnant Pacific slab, Fig. 1B) are integrated with a large dataset compilation for the post-110 Ma eastern Asia basalts (Supplementary Table S2) and experimental melts from carbonated and uncarbonated sources (Supplementary Table S3). The aims are to evaluate the possible role of older subduction episodes before the (Pacific) subduction in the genesis of this magmatic province and to explore the genetic link between mantle pyroxenites and recycled carbonates in the source of the intraplate basaltic magmatism.

2 Geological setting and data

The central-eastern Asia continent formed a coherent landmass by pre-Cretaceous subduction episodes involving ancient continental blocks (Fig. 1A; Zhao et al., 2018). These include the suturing of the archipelagic Paleo-Asian Ocean before 230 Ma along the Solonker Suture zone, and the closure of the Paleo-Tethyan Ocean before 320 Ma along the Qinling-Dabie-Sulu Orogenic

belt, and the westward subduction of the (Paleo-) Pacific plate since ~140 Ma (Wu et al., 2019). The subducted Pacific slab now is stagnant in the mantle transition zone and underlies a “big mantle wedge” (BMW) beneath eastern Asia (Fig. 1B; Huang and Zhao, 2006; Xu et al., 2018); the western leading edge of the slab approximately coincides with the surface location of the N-S trending gravity lineament in the North China Craton (NCC; Fig. 1A).

The post-110 Ma “diffuse” basaltic provinces extend far west of the gravity lineament (outside the BMW), and the presence of low- ^{26}Mg basalts at Huihe (He et al., 2019), high- ^{66}Zn basalts at Abaga and Chifeng (Liu et al., 2022), and high- $^{206}\text{Pb}/^{204}\text{Pb}$ basalts at Wudi (Sun et al., 2017) and Niutoushan (Qian et al., 2020) on both sides of the lineament (Fig. 1A), indicate contributions from older ancient subductions. The 89-81 Ma Langshan lamprophyre-basalt association lies outside the present-day BMW (Fig. 1B), but their elemental and Sr-Nd isotopic compositions are indistinguishable from those of the post-110 Ma basalts lying above the BMW (Fig. S1). The basaltic associations were considered to originate from highly similar pyroxenite-bearing asthenospheric sources fluxed by components from the subducted Paleo-Asian oceanic igneous crust (Dai et al., 2021a). The samples previously used for whole-rock major-, trace-element and Sr-Nd-Pb isotope analyses were selected here for Mg-isotope determination. The detailed methods are described in the Supporting Information. The results (Fig. 2A) show that the Langshan basaltic rocks are isotopically light ($^{26}\text{Mg} = -0.391$ to -0.513 ‰), analogous to their post-110 Ma equivalents directly above the BMW ($^{26}\text{Mg} = -0.24$ to -0.63 ‰).

3 Paradox of light Mg-isotope compositions vs whole-rock chemistry of the Langshan basaltic associations

Careful evaluation on the potential fractionation processes for Mg isotopes using the considerations in Liu and Li (2019) suggest that the light Mg-isotopic signatures of Langshan basaltic rocks are most likely inherited from the Mg-isotopically light mantle sources (Supporting Information). Such isotopic signatures are normally interpreted as evidence of recycled carbonates in the sources (Li et al., 2017) but paradoxical to the evidence from major elements.

The Langshan basaltic rocks are compared with compiled experimental melts of carbonated sources (peridotite, pyroxenite) and uncarbonated sources (peridotite, silica-deficient pyroxenite, hornblendite, phlogopite). Experimental melts of carbonated rocks generally have high $\text{CaO}/\text{Al}_2\text{O}_3$ ratios typically higher than 1.4 while those of uncarbonated lithologies are characterized by low $\text{CaO}/\text{Al}_2\text{O}_3$ (Fig. 2A). The Langshan basaltic rocks, and other basalts from eastern Asia are consistently characterized low $\text{CaO}/\text{Al}_2\text{O}_3$ (e.g., <1), thus indicating derivation from uncarbonated sources. Besides, basaltic rocks considered generally have high K_2O and low TiO_2 contents relative to those of the partial melts from carbonated sources (Fig. 2B). Instead, the detailed comparison with experimental melts (Fig. S2) and other experimentally calibrated geochemical proxies (Figs. S3 and S4) suggests that the Langshan

basaltic rocks and other low- ^{26}Mg equivalents in eastern Asia can be reasonably interpreted as originating from source domains containing silica-deficient pyroxenites (Supporting Information).

4 Reconciling the Mg-isotopic vs elemental paradox by decarbonation of altered oceanic crust

Altered oceanic crust usually have distinctly light Mg-isotopic compositions with ^{26}Mg down to - 1.70‰, due to precipitation and accumulation of carbonates (Huang et al., 2018). The carbonates will break down during subduction or in the upper mantle and liberate the isotopically light cations to the pyroxene-rich products (Dasgupta and Hirschmann, 2007; Stagno et al., 2013). The Mg-isotopically light pyroxenite/eclogite xenoliths reported in the eastern Asia and west Africa contain no carbonates and are considered as the transformation from decarbonated altered oceanic crust (Wang et al., 2015; Yu et al., 2021). Thus, presence of decarbonated altered oceanic crust in the mantle sources may serve as a tentative reconciliation of the paradox arising from the Mg-isotopic and major-element signatures of the basaltic rocks considered (Fig. 2). Here, the feasibility of this reconciliation is evaluated via qualitative consideration on linkage of low- ^{26}Mg signatures to the source pyroxenite and quantitative modelling on the melt Mg-isotopic compositions for adiabatic melting of pyroxenite-bearing source domains.

4.1 Linkage of basaltic low- ^{26}Mg signatures to pyroxene-rich source domains

Mantle decarbonation may occur via either (1) extraction of carbonate-bearing melts from mantle domains with remarkable solidus depression due to the presence of crystalline carbonates or (2) release of CO_2 vapor controlled by the carbonate ledge, the subsolidus silicate-carbonate reaction at relatively lowered pressures (Hammouda and Keshav, 2015). However, the two scenarios of decarbonation have contrasting effects on the trace-element budget of the sources. The decarbonated residua after melt extraction would be highly depleted in incompatible trace-elements because the extracted melts usually have high partition coefficients for most incompatible trace elements and would scavenge these elements in the source (Williams and Knittle, 2003; Dasgupta and Hirschmann, 2006). In contrast, the residua after release of CO_2 vapor would retain the original trace-element budget. In this context, the low- ^{26}Mg basaltic rocks considered here are highly enriched in incompatible trace element (e.g., REE= 334-488 ppm; Fig. S1) and thus would prefer enriched source domains like the residua left behind by release of CO_2 vapor. Moreover, the ^{26}Mg of the Langshan basaltic rocks are negatively correlated with TiO_2 contents, the proxy for melting degrees (Fig. 3A), and the FCKANTMS, the newly proposed indicator of pyroxenite contribution in the melt sources (Fig. 3B; Yang et al., 2019). That is, low-extent partial melts with high TiO_2 contents generally have low ^{26}Mg and contain high mass contributions from source pyroxenites (high

FCKANTMS values). These correlations suggest that the Mg-isotopic signatures of the basaltic rocks may be controlled by the relatively fusible pyroxenite embedded in the source domains.

The linkage of light Mg-isotopic signatures of the basaltic rocks to pyroxene-rich mantle sources remains reasonable when the P-T- f_{O_2} conditions are considered. Experimental studies have shown that the release of CO_2 from peridotitic systems generally occurs at <3 GPa given ambient mantle T- f_{O_2} conditions and much higher pressures (> 5 GPa) for pyroxenitic (basaltic) systems. The lithosphere of the Langshan area is 70-80 km thick, as constrained by seismic imaging (Chen et al., 2014) and the basalt-borne xenolithic suite (Dai et al., 2021b). Thermal condition of the lithosphere (Huang and Xu, 2010) and sub-lithospheric mantle (Dai et al., 2021b) are comparable to those for typical circum-craton regions worldwide (O'Reilly et al., 1997) and the ambient convecting upper mantle (Herzberg et al., 2010). Under such mantle conditions, the carbonate ledge requires that the decarbonation of peridotitic asthenosphere and the altered oceanic crust would take place via partial melting and release of CO_2 vapor, respectively. On this ground, the decarbonated altered oceanic crust would not only inherit the isotopically light Mg but also the highly enriched trace-element budget, and thus have the potential to produce partial melts with low- ^{26}Mg signatures and high contents of incompatible trace elements.

4.2 Modelling the melt Mg-isotopic compositions through adiabatic melting of pyroxenite-bearing sources

To quantitatively constrain the Mg-isotopic characteristics of partial melts from garnet pyroxenites (transformed from decarbonated altered oceanic crust)-bearing mantle, adiabatic melting modelling have been conducted on such lithologically heterogeneous mantle sources. The details on the modelling, including the initial conditions of the source domains, the adiabatic melting modelling, and the calculation of the adiabatic melt ^{26}Mg , are explained in the Supporting Information.

Figure 4 shows the modelled Mg isotopic composition of adiabatic melts extracted from source domains containing variable fractions (0%, 2%, 10%, 20%, 50%, and 100%) of Mg-isotopically light silica-deficient pyroxenites in peridotitic matrix. For the melting of peridotite, the adiabatic melts display ^{26}Mg ranging from around -0.358 to -0.380‰, all lower than the ^{26}Mg of the melting residua (Fig. 4A). The melt-residua isotope fractionation is caused by the preferential melting of garnet over the refractory phases like olivine and orthopyroxene, because garnet with a coordination number of 8 for Mg usually contains isotopically light Mg relative to coexisting mantle silicates (Huang et al., 2013). Similarly, the positive correlation between ^{26}Mg and melting depth is the result of increasing stability of garnet with depth. For the melting of silica-deficient pyroxenite with an assemblage of garnet, clinopyroxene and olivine (Fig. S3), the adiabatic melts have lowered ^{26}Mg ($<5‰$) compared to the initial Mg-isotopic composition ($^{26}Mg = -0.5‰$) of the pyroxenite, also due to the preferential

melting of the Mg-isotopically light garnet.

For the melting of peridotite-pyroxenite mixture, the adiabatic melts ^{26}Mg shift rapidly to low values with increasing fractions of Mg-isotopically light pyroxenites in the source (Fig. 4A). This is because the pyroxenitic mass contributions in the melt usually outweigh its fractions in the source (Fig. 4B) due to the preferential melting of pyroxenite over coexisting peridotite, especially when the heat transfer from refractory to fusible lithologies is considered (Brunelli et al., 2019). The negative correlation of adiabatic melt ^{26}Mg with depth (Fig. 4A) is primarily controlled by the increased pyroxenitic mass contributions in the melt with increasing melting depths (Fig. 4B). The results show that the Mg-isotopic characteristics of the Langshan basaltic rocks and most low- ^{26}Mg Cenozoic basalts from eastern Asia can be well explained by the adiabatic melting of source domains containing variable fractions of isotopically light pyroxenites, where the fraction is 2-5% for the Langshan basalts and up to 50% for the lamprophyres. Notably, the high pyroxenites fractions in the source of the lamprophyres align well with and thus cross-validate by our previous estimates (55 wt.% pyroxenites in the source) using trace elements (Dai et al., 2021a).

Taking together, the low- ^{26}Mg signatures of the Langshan lamprophyre-basalt associations suggest mass contribution from recycled carbonates while the low $\text{CaO}/\text{Al}_2\text{O}_3$ and high K_2O contents require uncarbonated source domains. This paradox can be well explained by the decarbonation of subducted altered oceanic crust via release of CO_2 vapor and the concomitant formation of residual, low- ^{26}Mg pyroxenites with high trace-element contents before involved in the sources of the basaltic rocks.

5 Carbonate recycling from superposed subductions in central-eastern Asia

The Langshan basaltic rocks are compositionally like the post-110 Ma equivalents across central-eastern Asia (Fig. S1). Available Mg-isotope data, including new data in this study, show that these basaltic rocks constitute a vast low- ^{26}Mg magmatic province in central-eastern Asia (Fig. 1A; Li et al., 2017; He et al., 2019), stretching significantly westward beyond the influence of the stagnant Pacific slab forming the current BMW (Fig. 1B). This magmatic province may record contributions from carbonate-bearing oceanic crust associated with repeated subduction events through time, especially when the following aspects are considered.

(1) The spatial variation in Zn isotope compositions of Cenozoic basalts west of the N-S trending gravity lineament (Fig. 1A; Abaga to Chifeng) suggests that the subduction of the Paleo-Asian oceanic slab should have injected carbonates into the asthenospheric sources (Liu et al., 2022). Moreover, radiogenic Pb-isotope compositions (e.g., $^{206}\text{Pb}/^{204}\text{Pb} > 18.5$, $^{208}\text{Pb}/^{204}\text{Pb} > 38.5$), typical of ancient recycled components, have now been recognized in basaltic rocks on both sides of the gravity lineament (Fig. 1A, e.g., Langshan, Dai et al., 2021a;

Niutoushan, Sun et al., 2017; Wudi, Qian et al., 2020). Accordingly, the asthenospheric sources of the vast post-110 Ma diffuse basaltic province should have been pervasively infiltrated by recycled components from older subduction episodes before the subduction and stagnation of (Paleo-) Pacific slab beneath eastern China.

(2) The subducted Paleo-Asian oceanic slab under Siberia Craton remains detectable more than 150 Ma after the subduction event (van der Voo et al., 1999); the relic of this subducted slab is also detected underneath the Western Junggar, Northwest China (Wu et al., 2018). These geophysical studies suggest that the convection of subcontinental asthenosphere should be highly sluggish. This is consistent with the knowledge arising from post-subduction arc-type magmatism that asthenosphere polluted by recycled components can remain semi-stationary relative to the overriding lithosphere for tens of million years (van Hinsbergen et al., 2020). Thus, the recycled components from superposed Phanerozoic subductions may still reside in the asthenosphere beneath central-eastern Asia.

(3) Recent seismic studies show that deep asthenosphere in central-eastern Asia is generally characterised by low seismic velocities (Zhao, 2021; Li et al., 2022a). This low-velocity anomaly can extend westward beneath the Western Junggar basin and has been interpreted as partial melting induced by addition of volatile components from ancient subducted slabs (Li et al., 2022b). This interpretation is in accordance with repeated subduction events in the prolonged construction of the Eurasian continent (Zhao et al., 2018). Therefore, the recycled components in mantle sources of the vast low- ^{26}Mg basaltic province across central-eastern Asia should not be ascribed to any single subduction event but are causally linked to multiple subduction episodes.

6 Ubiquitous subduction-related decarbonation and pyroxenite formation in the upper mantle

The central-eastern Asia continent became an intraplate setting after the pre-Cretaceous amalgamation of various ancient blocks (Zhao et al., 2018). The post-110 Ma diffuse basaltic activities covering this vast continent (Fig. 1) usually have similar elemental and isotopic (Sr-Nd-Pb-Mg) signatures (Figs. S1 & 2) and are derived from asthenospheric domains underneath thin lithosphere (70-100 km, Supporting Information). Based on these tectonic and geochemical similarities, we infer that decarbonation of altered oceanic crust and concurrent formation of isotopically distinct pyroxenites recognized in the sources of the Langshan basaltic rocks should be a prevailing process in asthenospheric sources for the vast low- ^{26}Mg basaltic province. That is, carbonate precipitated in the altered oceanic crust from repeated subduction events (Zhao et al., 2018) should have broken down and liberated isotopically light Mg to the transformed garnet pyroxenite before involvement in the melt generation.

Moreover, global small-volume intraplate continental basaltic rocks generally

share similar melting conditions, with mantle potential temperatures of ~1400 °C and final melting depths of 70-100 km (Lee et al., 2009). Under such conditions, the recycled carbonates would break down to release CO₂ vapor due to the reaction with associated silicates in the altered oceanic crust, leaving behind residual (decarbonated) pyroxenite-rich domains containing the isotopically distinct cations originally bound to the carbonates (Stagno et al., 2013; Dasgupta et al., 2013). We suggest that the subducted-related decarbonation and concurrent pyroxenite formation should be a ubiquitous process that can explain the pyroxenitic contribution in many other low- ²⁶Mg intracontinental basaltic provinces worldwide. Therefore, the integration of isotope data with major- and trace-elements and mantle conditions are necessary for the identification of the deep carbon cycling in paleotectonic regimes and the re-evaluation of mass fluxes through Earth’s different layers.

7 CONCLUSIONS

The Langshan associations have light Mg-isotopic compositions (²⁶Mg = -0.391 to -0.513 ‰) like those of recycled carbonates but display low CaO/Al₂O₃ and high K₂O contents paradoxically resembling those of partial melts from uncarbonated sources. Negative ²⁶Mg *vs* FCKANTMS (pyroxenite marker) correlation and thermodynamically constrained melting modeling on pyroxenite-peridotite mixtures suggest the presence of low ²⁶Mg pyroxenite in the melt source that can be interpreted as transformation from decarbonated altered oceanic crust. This model can explain pervasive pyroxenitic contributions in the post-110 Ma low- ²⁶Mg intraplate basaltic extrusions across eastern Asia related to superposed multiple subduction episodes and can be applied to many other similar basaltic provinces worldwide. This ubiquitous subduction-related decarbonation processes have important implications for global deep carbon cycling.

Open Research

The data archiving of the Supplementary Tables S1-S4 in this study is underway in the Mendeley Data.

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Figure and captions

Figure 1. (A) Distribution of post-110 Ma magmatic province in central-eastern Asia (here defined as the regions on each side of the N-S trending gravity lineament (dark pink dashed line)) with major Phanerozoic tectonic boundaries. The 50-110 Ma and <50 Ma basaltic rocks are indicated by red crosses and irregular shapes filled in dark green, respectively. Triangles highlight those with Mg isotope data from the literature (yellow) and this study (pink). (B) Western Pacific-eastern China mantle P-wave tomography sections at the latitudes of 41°N and 37°N (modified from Huang and Zhao, 2006). The big mantle wedge refers to mantle domain above the stagnant slab.

Figure 2. (A) ^{26}Mg vs $\text{CaO}/\text{Al}_2\text{O}_3$ (weight ratios) and (B) K_2O vs TiO_2 contents of the Langshan basaltic rocks and the post-110 Ma equivalents from

eastern China (shown as triangles in Figure 1A). The inset histogram in (A) shows experimental melt $\text{CaO}/\text{Al}_2\text{O}_3$ of carbonated and uncarbonated sources (Supplementary Table S3), where the colors of axis scales keep the same as those of the corresponding data series.

Figure 3. Correlations of ^{26}Mg with TiO_2 (A) and FCKANTMS (B) for the Langshan basaltic associations. FCKANTMS, a combination of log-ratios involving all major elements, is a recently-proposed indicator of pyroxenite contribution in the mantle source of basaltic rocks (Yang et al., 2019).

Figure 4. (A) ^{26}Mg and (B) pyroxenitic mass contributions for adiabatic melts extracted from source domains with a potential temperature of 1400 °C and containing variable pyroxenite fractions source domains. The melting pressure of the basaltic rocks are the same as those in Figure S4B according to Herzberg (2011). The percentages aside the gradient color curves in (A) and (B) denote pyroxenite fractions in the sources. The discussion and details on the modeling are included in the text and Supporting Information, respectively.