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Where on the Moon was the eruption that produced the recently reported ~ 120 million year old volcanic glass beads?

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ABSTRACT

Three anomalously young, ~120 Ma old lunar mare pyroclastic beads have recently been reported (Wang et al., 2024) from Chang'e-5 (CE-5 soils, particularly distinguished from impact melt beads by sulfur isotope ($^{34}S/^{32}S$) composition and correlations with sulfur concentration. We examine lunar pyroclastic eruption theory and candidate eruption conditions in order to locate the vent and assess its geological context, finding that the estimated maximum pyroclast dispersal range from a candidate source vent is likely to be ~200 km, placing it within the area of the CE-5–2.0 Ga sampled Em4 unit. The greatest predicted dispersal distances are associated with an explosive eruption from a stalled dike several kilometers below the surface, creating an elongated, multi-km-scale pit crater potentially surrounded by a dark pyroclastic ring. We assessed the Chang'e-5 region for such candidates and found none. This raises the possibility that the ~120 Ma pyroclastic beads might have been delivered to the site from an impact crater outside Em4, but the most likely candidates are sufficiently large and at such great distances that they are likely to have reset the ages of any young pyroclastic beads thus delivered. Lacking a clear source for extraordinarily young pyroclastic beads, we reassess the possibility that the ~120 Ma beads may be of local impact melt origin. Evidence favoring this hypothesis includes the abundant CE-5 impact glass bead ages in the 100–200 Ma year range previously reported (Long et al., 2022), and the similarities in composition and characteristics of the three beads and those of local impact origin. To address these conundra, further regional searches for a source vent and continued geochemical characterization and dating of CE-5 regolith glass beads should be undertaken.

1. Introduction and background

The Moon is a laboratory for the study of the first half of Earth history, largely destroyed by plate tectonics and obscured by erosion. One-fourth the diameter of Earth, it loses heat much more efficiently by conduction. Its lithosphere thickened rapidly, making the Moon a "one-plate planet" whose stable surface preserves and reveals the geological processes operating during earliest planetary history. Critical among these(Fig. 1) are the effects of the early impact bombardment on melting the outer parts of the Moon (lunar magma ocean, LMO), the density segregation of minerals during LMO solidification to produce the crust, the sinking of the denser residue to the deeper interior, and how these events set the stage for the further thermal evolution of the interior (New Views of the Moon 2, 2023).

As with the Earth and other rock-dominated planetary bodies, the geological record of the location, style and magnitude of volcanism is a proxy for the global cooling and thermal state of the Moon. Tectonic features indicate that cooling was rapid and that the global state of stress in the lithosphere changed from net extensional (up to ~20 MPa) to net compressional (also up to ~20 MPa) ~3.5 Ga ago (Solomon and Head, 1980), during the peak of mare basalt eruptions (Fig. 1). Seismic data and geophysical models indicate that subsequently the lunar lithosphere increased in thickness to its current ~1000 km value, ~56 % of the Moon's radius. Further evidence of this global cooling is a parallel decrease with time in the volume of mantle-derived mare basalt melts extruded to the surface, and an apparent absence of volcanic rocks erupted to the surface in the last billion years (Head et al., 2023, their Fig. 2), all evidence of a Moon that had nearly solidified throughout by that time (Fig. 1). This current scenario for the thermal evolution of the Moon (New Views of the Moon 2, 2023) has recently been challenged by

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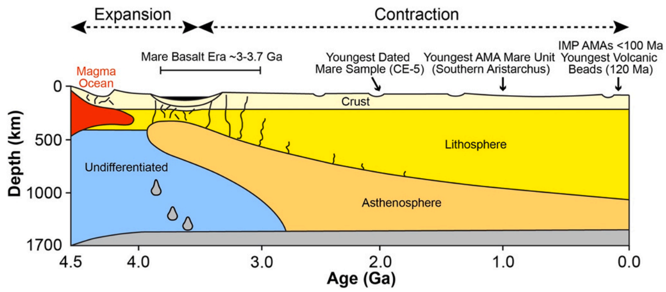

Fig. 1. Lunar thermal evolution: Accretion led to extensive deep melting and a magma ocean, forming the anorthosite flotation crust. Subsequent radioactive decay induced mantle melting and ascent and eruption of mare basalt magmas. Conductive heat-loss to space led to an increasingly thick lithosphere, reaching a present-day thickness of ~1000 km. Early slight expansion was followed by cooling and later contraction. Concurrent with global cooling and contraction, volcanism declined with time and apparently ceased between 1 and 2 Ga. (2.0 Ga date, Che et al., 2021; Li et al., 2021; 1.0 Ga youngest Absolute Model Age (AMA), Stadermann et al., 2018). IMP <100 Ma AMAs, Braden et al. (2014); 120 Ma CE-5 pyroclastic beads, Wang et al. (2024), occur within the last <3 % of lunar history. Modified from Christiansen and Christiansen and Spilker (2024), with permission.

the discovery of small, apparently very young occurrences of mare basalt deposits termed Irregular Mare Patches (IMPs), dated stratigraphically and by crater counting to <100 Ma (Braden et al., 2014), and Ring-Moat Dome Structures, similarly dated to less than several 100 Ma (Zhang et al., 2021)(Fig. 1). These ages are the subject of current debate (e.g., Qiao et al., 2021).

1.1. New developments

Recently, three volcanic glass beads returned by the Chang'e-5 mission and interpreted to be of pyroclastic origin have revealed exceptionally young laboratory U—Pb radiometric formation ages of ~120 Ma (Wang et al., 2024), adding significant support to evidence for geologically current interior activity on the Moon.

Wang et al. (2024) studied ~3000 glass beads from CE-5 regolith soils and found three that they interpreted as pyroclastic in origin. Because it is so difficult to distinguish pyroclastic beads from glass beads of impact origin (they generally have similar chemical and isotopic compositions), Wang et al. (2024) applied standard criteria, but were unable to establish any definitive differences between possible pyroclastic glass beads and those interpreted to be of impact melt origin. They then applied multiple additional criteria (evidence of incomplete melting and high and variable concentrations of elements (e.g., Ni) that are likely to have originated from an impactor) to identify 13 volcanic glass candidates among the ~3000 glass beads. These were further assessed using sulfur isotope ($^{34}S/^{32}S$) composition and correlations with sulfur concentration, determinations that could provide additional evidence to distinguish pyroclastic from impact glasses. Wang et al. (2024) identified three glass beads that they interpreted to be of volcanic origin on the basis of combined evidence from mineralogy, chemistry, sulfur isotopes, and extraordinarily radiogenic Pb isotopes. These three glass beads yielded U—Pb ages of ~120 Ma.

Description of the three glass beads (Wang et al., 2024) provides several lines of evidence for distinguishing them from impact-generated glass beads (Delano, 1986), and from the 37,000 km^2, ~2 Ga Em4 mare basalt unit (Qian et al., 2021) from which most of the CE-5 regolith sample was derived. The Wang et al. (2024) description supports the interpretation that the three glass beads are of explosive volcanic (pyroclastic) origin, delivered to the sampling site from a 120 Ma eruption elsewhere on the Moon (Wang et al., 2024). Critically important to further verification of recent lunar volcanism is the identification of the source vent and geological context of these glass beads. How far away from an explosive eruption site can pyroclasts be propelled? Locating the distance to the eruption site requires knowledge of lunar basaltic eruption dynamics (e.g., Rutherford et al., 2017; Morgan et al., 2021;

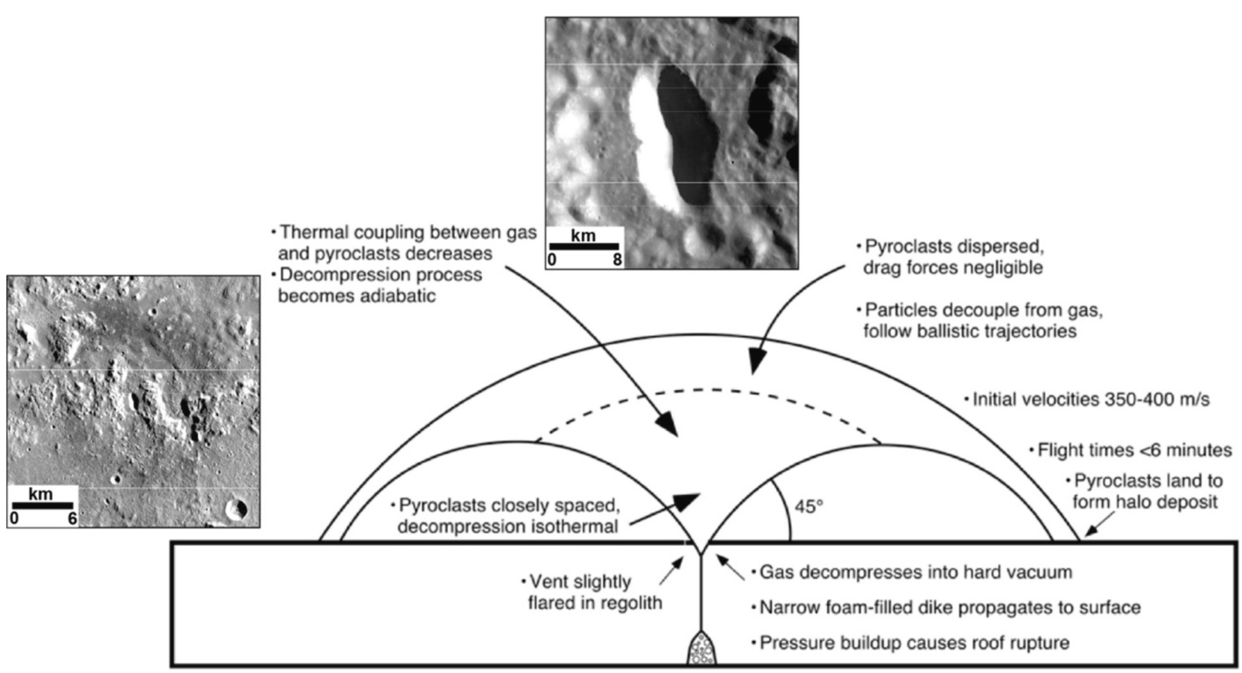

Fig. 2. Orientale O-ring-type eruption. The Orientale dark ring (left inset) has been modelled (Head et al., 2002) as a pyroclastic eruption originating at a fissure now marked by a 7.5 × 16 km pit crater (middle inset) at its center, emanating from a dike stalled at ~3–4 km depth that formed an upper foam layer and built up pressure, exceeding the tensile strength of the overlying rocks, and initiating an eruption into the lunar vacuum. This produced an ~38–54 km high, symmetrical umbrella-shaped ballistic spray of pyroclasts at velocities of ~350 to ~420 m/s, causing glass bead deposits to accumulate preferentially in a ring representing the material ejected at ~45°, and forming the visible annular ring. No associated lava flows are observed. Maximum pyroclast dispersal distance could be as much as 200 km.

Wilson and Head, 2003, 2017, 2018; Head and Wilson, 1992, 2017). Here we summarize possible modes of volcanic glass bead formation and dispersal and suggest avenues for identifying their source regions on a possibly recently volcanically active Moon.

1.2. Pyroclastic activity and pyroclastic bead dispersal associated with typical mare basalt eruptions

Typical volatile-containing mare basalt magmas proceed through a four-stage eruption sequence following the propagation of the feeder dike from the source region to the site of the surface eruption (Wilson and Head, 2018, their Fig. 1). The dike tip is predicted to contain an upper pure gas zone extending down to a few hundred meters, above a highly vesicular foam layer, extending downward for an additional several hundred meters (Wilson and Head, 2003, their Fig. 1). As the dike tip reaches the surface, Phase 1 begins with the pure gas zone venting at speeds up to 1000 m/s, propelling any entrained near-surface regolith material to hemispherical distances. Immediately afterwards, the several hundred meter zone of highly vesicular foam underlying the dike tip gas cavity will explosively vent to the surface vacuum, creating a widespread, but extremely thin deposit (Head and Wilson, 2017). On the Moon, the lack of atmosphere causes lateral as well as vertical acceleration of the gas, producing an umbrella-shaped eruption plume similar to those seen on Io. Complete eruption of the gas-rich magma in the vesicular zone would have taken as little as 3 min and glass bead dispersal distances could be up to several tens of km. This latter part of eruption Phase 1 is likely to be the source of the ubiquitous exotic volcanic glass beads found in highland and mare soils (Delano, 1986). It is also a candidate mechanism for the eruption of the CE-5 pyroclastic beads. In Phase 2, the base of the dike continues to rise toward neutral buoyancy and a high-flux (~10^6 m^3/s decreasing toward 10^5 m^3/s) hawaiian-style fire-fountain eruptive phase ensues. Submillimeter-sized pyroclastic droplets in the fountain lose gas efficiently, accumulating within a few km of the fissure with negligible cooling, to form a vesicle-deficient lava lake, overflowing to form a lava flow, and potentially a sinuous rille in the case of a sufficiently long-lasting eruption (Fig. 1a). In Phase 3, the now neutrally-buoyant dike feeds a lower-flux hawaiian-to-strombolian transition phase producing flows and local, near-vent, strombolian pyroclastic deposits. Finally, as the dike closes, Phase 4 involves intermittent strombolian near-vent activity accompanying vesicular lava flow formation.

If the three 120 Ma CE-5 pyroclastic beads are from either Phase 1–2 or even Phase 3–4 of a recent eruption, the source vent should be in the immediate vicinity of the CE-5 site, within ~30 km, and is highly likely to have one or more typical features associated with such a lunar eruption (e.g., pyroclastic mantle, lava flow fields, possible sinuous rille, strombolian spatter cone) (Wilson and Head, 2018; Head and Wilson, 2017).

1.3. Pyroclastic activity and pyroclastic bead dispersal associated with orientale O-ring style eruptions

A different type of explosive volcanic eruption is exemplified by a large, 154 km-diameter dark annular ring, located in the south-southwestern part of the Orientale basin, and centered on an elongate 7.5 km by 16 km depression (Head et al., 2002) (Fig. 2, insets). Remote sensing UV–visible data indicate that the ring deposit consists of pyroclastic glasses (Weitz et al., 1998). The Orientale dark ring has been modelled (Head et al., 2002) to be the manifestation of a pyroclastic eruption originating from a fissure vent that subsequently collapsed to form the 7.5 × 16 km pit crater now located at the ring center. The event began with rapid emplacement of a dike from subcrustal depths to within ~3–4 km of the surface (Fig. 2). As the dike stabilized and degassed predominantly carbon monoxide over ~1.7 years, it formed an upper foam layer, building up pressure until it exceeded the tensile strength of the overlying rocks, which then caused a dike to penetrate to the surface to produce an eruption lasting ~1–2 weeks. The eruption into the lunar vacuum produced a ~ 38–54 km high, symmetrical umbrella-shaped ballistic spray of pyroclasts at velocities of ~350 to ~420 m/s. The geometry of the eruption caused the deposits to accumulate preferentially in a ring representing the material ejected at ~45°, forming the visible annular ring. No associated lava flows are observed. Maximum pyroclast dispersal in this kind of eruption could be as much as 200 km and the rapid chilling of the pyroclasts into glass beads interpreted from the remote sensing data is consistent with this mode of eruption (Weitz et al., 1998). Head et al. (2002) attributed the paucity of pyroclastic rings of this type on the Moon to the low probability of a dike stalling at just the right depth (~3–4 km) during the peak period of mare volcanism to create these eruption conditions. Impact gardening of the lunar surface may also help to make such rings unrecognizable, but a search for pit craters like the one centered on the O-ring in Orientale may reveal additional source vents for this type of eruption. The specific age of the Orientale pyroclastic ring is unknown, but it is likely to have erupted sometime during the range of mare volcanism within the Orientale Basin (3.70–1.66 Ga; Whitten et al., 2011). This suggests that any O-ring type eruption occurring in the last ~120 Ma should be characterized by a large pit crater and a preserved pyroclastic ring.

1.4. Additional clues to ~ 120 MA pyroclastic bead origin

Finally, additional clues about the possible provenance of the three 120 Ma-old pyroclastic beads come from their morphology, shape, size, mineralogy and elemental abundances. The three picritic glass beads differ from the 25 previously identified classes of Apollo glass beads (Delano, 1986) in being characterized by high Na_2O, K_2O, P_2O_5 and incompatible elements, including REE and Th, suggesting high abundances of KREEP in the mantle source region (Wang et al., 2024). This may indicate a mantle source beneath the Procellarum-KREEP Terrane (PKT) (Jolliff et al., 2000; Elardo et al., 2024). However, on the basis of the uncertainty of the configuration of the subsurface crust and mantle below the PKT (see Zhang et al., 2023, for a discussion of the stratigraphy), and the lack of evidence for KREEP involvement in the mantle source for the CE-5 basalts (e.g., Tian et al., 2021, 2023), we feel that the bead KREEP-enrichment is not sufficiently definitive to confine the source vent to within the PKT boundaries. Nonetheless, additional source-vent searches should be conducted there, as the surface mare basalts may not be petrogenetically related to co-located pyroclastic deposits as is the case with Apollo 15 green glass beads and Apollo 17 orange glass beads (Neal et al., 2023).

In terms of bead shape, beads 1 and 2 are round, while bead 3 is bulbous-shaped with the smaller end broken, indicating aerodynamic shaping and solidification during flight in either magmatic gas flow or impact-induced vapor clouds. The grain size of the three beads (maximum dimensions) are ~50, ~38 and 60 μm respectively, falling toward the lower end of the Apollo pyroclastic bead size distribution (Morgan et al., 2021; their Fig. 1b). In modelling the formation and dispersal of pyroclastics on the Moon, Morgan et al. (2021) showed that the generation of CO gas bubbles at much greater depths and pressures than bubbles of other volatiles produces bimodal (~120 and 650 μm) total pyroclast size distributions. The complicated gas-particle interactions in the ultra-low pressure expanding gas stream then lead counter-intuitively to the median grainsize in pyroclastic deposits first increasing, then decreasing, and finally increasing again, with increasing distance from the vent. This trend differs from a monotonic decrease, as is the case where an atmosphere is present, and reduces the chance of using droplet size to determine travel distance. In terms of impact-induced gas flow, Long et al. (2022a) estimated the maximum ballistic transport distances as a function of crater size for observed impacts within the Em4 unit (their Fig. 4), and calculated the probability of finding impact glass beads at the CE-5 site from specific local craters in Em4 (their Fig. 5). Relative to more distant crater origins, Johnson and Melosh (2014) modelled the formation of melt droplets during larger hypervelocity impacts, tracking the motion of impact ejecta and estimating the size of the ejecta products, predicting a decrease in melt droplet size with increasing crater size and ejection velocity (their Fig. 3).

2. Discussion

We conclude that the most likely eruption scenario for the reported ~120 Ma pyroclastic beads is related to an Orientale dark pyroclastic ring-like eruption (Fig. 2). Three factors favor this interpretation: 1) The ~120 Ma age which would place the event in the time of the thickest lithosphere and the most highly compressive global stress state (Fig. 1). 2) In turn, this would favor the stalling of a late-Copernican-age dike at several kilometers depth in the crust, in contrast to the range of dike penetration levels in the earlier peak volcanism period (Head and Wilson, 2017, their Fig. 16). 3) Such an eruption (Fig. 2) is predicted to lack associated near-vent lava flows, deposits that might reveal the source through a corresponding 120 Ma crater count date. Thus, the most promising candidates for the source vent (Fig. 2) are predicted to be a morphologically fresh, kms-scale circular-to-elongated pit crater, perhaps among the class of pit craters identified by Wagner and Robinson (2014), surrounded by a pyroclastic ring.

We plotted the radial ranges predicted for pyroclastic eruptions on a map of the Chang'e-5 landing site and region (Fig. 3, yellow dished circles). This clearly shows that the vast majority of the area within the predicted maximum range, the ~200 km radius circle, lies within the ~2 Ga unit Em4, the source of the regolith (Qian et al., 2021). We found no evidence for the presence of an Orientale O-ring-type, kms-scale pit

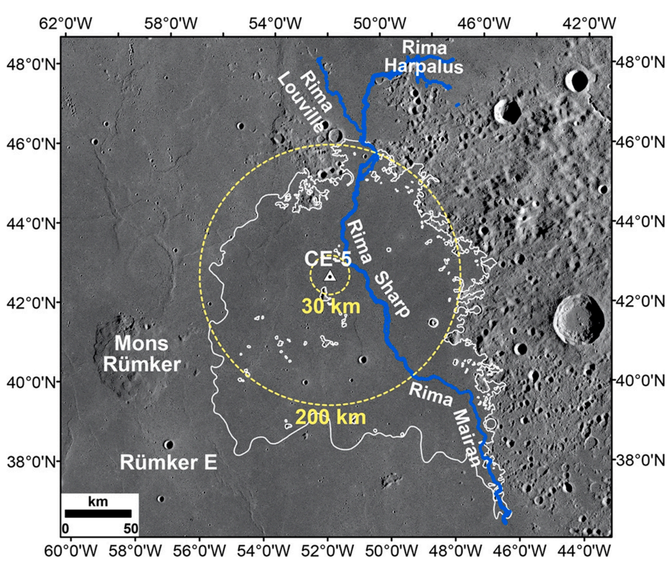

Fig. 3. Maximum dispersal distances from selected lunar explosive eruption types superposed on the CE-5 region, showing the actual landing site (white triangle) in the central part of unit Em4 (irregular solid white line), and sinuous rilles (blue lines). The rough pitted terrain to the east is part of the adjacent circum-Imbrium basin uplands, and is strewn with secondary craters/crater chains from the Early Imbrian-aged Iridum Basin to the northeast. Superposed on the landing site are two circles (yellow), one (30 km radius) representing maximum predicted pyroclast range for typical mare basalt eruptions (Wilson and Head, 2018), and the other (200 km radius) representing maximum predicted range for Orientale O-ring-type eruptions (Head et al., 2002). Note that there is no evidence within 30 km for a ~ 120 Ma eruption (e.g., vents, pyroclastics, small cones, flows) superposed on the ~2 Ga-age, Em4 unit underlying the landing site. In addition, the vast majority of the area within the 200 km-radius circle is composed of the 2 Ga-old Em4 unit, and no potential O-ring-type source pits (Fig. 2, center inset) have yet been observed within, or in the vicinity of this circle. Base map after Qian et al. (2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

crater, or surrounding dark pyroclastic ring (Fig. 2) within this range. However, additional searches should be conducted for smaller, more inconspicuous, source vents in the region.

This raises several possibilities:

1) An O-ring-type source eruption might have been larger than the one modelled (Fig. 2) for the deposit south of Mare Orientale, and thus outside the 200 km radius area. This is an option potentially favored by the up to ~20 MPa net compression late in lunar history (Solomon and Head, 1980), and the implied large dike size necessary to reach the near-surface.

2) The three pyroclastic glass beads may have formed, and been delivered to the site, by eruptions related to the emplacement of nearby Irregular Mare Patches (IMPs) (see Fig. S12 in Wang et al., 2024), interpreted to have formed geologically recently, the three largest in the last 100 Ma (Braden et al., 2014).

3) The three pyroclastic glass beads may have formed due to pyroclastic eruptions elsewhere on the Moon, but were delivered to the site by an impact that formed at a time later than the ~120 Ma pyroclastic bead age. Qian et al. (2021; their Table 1) located six impact craters in the region that formed at a time later (27–98 Ma) than the ~120 Ma bead age, but all six of these impacted into target units much more ancient than ~120 Ma, and their distances from the CE-6 site are sufficiently large that the impact event is likely to have reset any original pyroclastic bead ages (e.g., Long et al., 2022b).

4) The CE-5 droplets interpreted as ~120 Ma pyroclastic beads may actually be from a closer location and locally impact-derived, with their ages reset by these local impacts. Indeed, evidence favoring this hypothesis includes the abundant CE-5 impact glass bead ages in the 100–200 Ma range previously reported (e.g., Long et al., 2022a). Additional analysis of CE-5 glass beads should be undertaken to more confidently distinguish between those of potential pyroclastic origin (Wang et al., 2024) and those of impact origin (e.g., Long et al., 2022b).

3. Conclusions

Anomalously young, ~120 Ma lunar mare pyroclastic beads have recently been reported from Chang'e-5 soils returned from northern Oceanus Procellarum. In order to locate their vent and geological context, we examined lunar pyroclastic eruption theory and candidate eruption conditions for the beads. We find that the estimated maximum pyroclast dispersal range from a candidate source vent is likely to be within 200 km, largely within the area of the CE-5–2.0 Ga sampled Em4 unit. The greatest predicted dispersal distances are associated with an explosive eruption from a dike stalled at several kilometers depth within the lunar crust (Fig. 2). Elongated, multi-km-scale pit craters within a radius of ~200 km are the best candidates to mark such an eruption site and we assessed the Chang'e-5 region for candidates and found none. This raises the possibility that the ~120 Ma pyroclastic beads might have been delivered to the site by more distant impacts beyond Em4, but the most likely candidates are sufficiently large (23–94 km) and at such great distances (~300–1200 km) that they are likely to have reset the ages of any young pyroclastic beads delivered, and their ages are all >280 Ma (Qian et al., 2021), much older than the ~120 Ma pyroclastic beads.

Lacking a clear source for extraordinarily young pyroclastic beads, we reassess the possibility that the ~120 Ma beads may be of local impact melt origin. Evidence favoring this hypothesis includes the abundant CE-5 impact glass bead ages in the 100–200 Ma year range previously reported (Long et al., 2022a), and the similarities of the compositions of the ~120 Ma glass beads interpreted to be pyroclastic on the basis of sulfur isotopic evidence and those interpreted to be locally derived and of impact origin (Wang et al., 2024).

To address these conundra, and help assess the reported extraordinarily young ~120 Ma basaltic pyroclastic volcanism, further regional searches for a source vent, and geochemical characterization and dating of CE-5 regolith glass beads, should be of the highest priority.

The question of whether lunar volcanism extends into the last few hundred million years is critical to fully understanding the thermal evolution of the Moon (Fig. 1) and other planetary bodies. Fortunately, to assist in this quest, NASA has selected the DIMPLE in situ radiometric dating experiment (Anderson et al., 2024) to date the ~33 Ma AMA Ina IMP on a Commercial Lunar Payload Services (CLPS) Mission later in this decade. Together with further assessments from orbital assets, such as the NASA Lunar Reconnaissance Orbiter, this age conundrum may soon be resolved.

CRediT authorship contribution statement

James W. Head: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Lionel Wilson:** Writing – review & editing, Formal analysis. **Yuqi Qian:** Writing – review & editing, Investigation, Formal analysis.

Declaration of competing Interest

The authors declare no competing interests.

Data availability

No data was used for the research described in the article.

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