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Small-scale lunar farside volcanism

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ABSTRACT

We identified and mapped 28 mare basalt occurrences, between the Australe and South Pole-Aitken basins on the southern lunar farside, and determined their absolute model ages (AMAs) by performing crater size–frequency distribution (CSFD) measurements. Our study area can be subdivided into seven major mare basalt occurrences in and around Bolyai, Roche V, Rosseland, Pauli, and Roche craters, south of both Rosseland and Coblentz craters, as well as mare patches between Eötvös and Roche craters. The AMAs of the mare basalts in and around Bolyai crater range from 2.1 Ga to 3.5 Ga (two units), varying drastically within short distances. The mare patches south of Coblentz crater contain nine units that have AMAs ranging from 2.1 Ga to 3.8 Ga. The mare basalts in Roche V crater show an AMA of 2.2 Ga. We mapped seven volcanic units in Rosseland crater and derived AMAs for five of these units. The mare basalts in Rosseland crater show the youngest AMAs found in our study area, ranging from 1.5 Ga to 2.9 Ga. The mare basalt occurrence south of Rosseland crater shows significantly older ages with an AMA of 3.3 Ga. The mare basalts in Pauli and Roche craters show AMAs from 1.7 Ga to 3.1 Ga. The mare patches between Eötvös and Roche craters show a similar range of AMAs from 1.9 Ga to 3.1 Ga. The AMAs of the mare basalts in our study show that the lunar farside was volcanically active for nearly as long as the lunar nearside (1.2 Ga ago), or at least longer than previously thought (2.5 Ga ago) and predicted by models of the ascent and eruption of lunar basalts. In addition, we calculated thicknesses and volumes of the investigated mare basalts. With thicknesses between ~21 m and ~172 m and volumes from ~0.1 km^3 to ~379 km^3, the mare basalts in our study area show a wide range of dimensions, similar to other mare basalts of the lunar near- and farsides.

1. Introduction

To understand the thermal evolution of the Moon it is essential to investigate the volcanic history of both the lunar near- and farsides. While the lunar nearside has been widely modified by mare volcanism, the farside shows only a few isolated mare deposits within the large craters and basins, such as the South Pole-Aitken (SPA) basin or Tsiolkovsky crater (e.g., Head, 1976; Wilhelms and El-Baz, 1977; Stuart-Alexander, 1978; Head and Wilson, 1992). Since the first discoveries of the asymmetry in volcanic activity between the near- and farsides by the Luna 3 mission in 1959, the origin of this asymmetry has been debated (e.g., Head, 1976; Head and Wilson, 1992; Zuber et al., 1994; Neumann et al., 1996). One early explanation was a presumed asymmetry of the occurrence of impact basins and large craters that might have influenced the emplacement of the mare (e.g., Head, 1976). While studies by Stuart-Alexander and Howard (1970) and Hartmann and Wood (1971) showed that there is no asymmetry in the distribution of lunar basins between the near- and farsides, a recent study by Miljković et al. (2013), using Gravity Recovery and Interior Laboratory (GRAIL) data, has shown that there are more large impact basins on the nearside than on the farside. Assuming that, due to the enrichment of heat-producing elements (KREEP), the crust and the upper mantle on the nearside were hotter than on the farside when the larger basins were formed, Miljković et al. (2013) proposed a model, which predicts the formation of impact basins twice as large on the nearside than on the farside, for similar-sized impacts. The difference in crustal thickness between the near- and farsides might also be an explanation for the asymmetrical distribution of mare deposits (e.g., Roberson and Kaula, 1972; Kaula et al., 1974; Head, 1976; Head and Wilson, 1992). Also using GRAIL data, Wieczorek et al. (2013) calculated the differences in crustal thicknesses between the near- and farside in unprecedented detail. While large areas of the lunar nearside (maria) show crustal thicknesses thinner than 35 km, most of the lunar farside highland crust is thicker than 45 km (Wieczorek et al., 2013). In contrast, most of the larger impact craters in both hemispheres show crustal thicknesses <1 km (Wieczorek et al., 2013). Especially in and around the SPA basin,

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the farside has crustal thicknesses similar to those beneath nearside maria. The origin(s) for the differences in crustal thicknesses and the occurrences of volcanic activity between the near- and farsides is of crucial importance in understanding the thermal evolution of the Moon.

The extensive mare volcanism of the lunar nearside has already been studied in great detail by numerous authors on the basis of Lunar Orbiter, Apollo mission data, and other data (e.g., Shoemaker and Hackman, 1962; Head, 1976; Wilhelms, 1987; Hiesinger et al., 2000, 2002, 2003; Heather et al., 2003; Bugiolacchi and Guest, 2008; Hiesinger et al., 2010, 2011; Staid et al., 2011; Kaur et al., 2014; Zhang et al., 2014; Varatharajan et al., 2014). New high-resolution data collected by the Lunar Reconnaissance Orbiter (LRO) and the SELENE (Kaguya) Terrain Camera (TC) now allow us to investigate the stratigraphy of the lunar farside in unprecedented detail. For example, Haruyama et al. (2009) determined model ages of mare deposits located at the southern lunar farside around and inside the South Pole-Aitken and Moscoviense basins. Morota et al. (2009, 2010, 2011) performed new crater size–frequency distribution (CSFD) measurements of mare deposits at the central region of the northern farside in the Orientale and Moscoviense basins. The studies by Haruyama et al. (2009) and Morota et al. (2009, 2010, 2011) are all based on Kaguya TC images (10 m/pixel).

Mare volcanism on the lunar nearside was active for about 3 Ga, lasting from ~4.2 Ga to ~1.2 Ga (Hiesinger et al., 2011). In contrast, absolute model ages (AMAs) of lunar farside basalts indicate that on the farside volcanism mostly ceased at ~3.0 Ga (Haruyama et al., 2009). However, Haruyama et al. (2009) also found mare deposits that show much younger model ages of ~2.5 Ga. Consequently, they concluded that farside volcanism might have occurred episodically, around 2.5 Ga and between 3.0 Ga and 3.6 Ga. However, they pointed out that the absence of volcanic deposits with ages between 2.5 and 3.0 Ga might also be explained by continuous superposition by younger deposits. Haruyama et al. (2009) argued that the difference in the termination of volcanic activity between the nearside (1.2 Ga) and the farside (2.5 Ga) might be related to a larger crustal thickness on the lunar farside, which hinders magma from reaching the surface. This has also been proposed before by Solomon (1975), Head (1976), and Head and Wilson (1992).

Volcanic samples of the Moon brought back by the Apollo and Luna programs show radiometric ages between 2.93 Ga and 3.8/4.35 Ga (e.g., Papike et al., 1998; Terada et al., 2007; Elardo et al., 2014), which is a much narrower range than the AMAs based on CSFD measurements. Thus, new volcanic samples from the Moon might be needed to test the young volcanic activity revealed by CSFD measurements based on remote sensing technics.

Our study addresses the following questions: (1) What was the timing of small-scale mare volcanism on the southern lunar farside? (2) Was volcanism on the lunar farside continuously or episodically active? (3) What are the differences in the timing of the volcanic activity between the lunar farside and nearside? (4) What is the volcanic flux of the mare basalts in our study area? (5) What can small-scale mare volcanism on the lunar farside tell us about the thermal evolution of the Moon?

1.1. Geological context

Our study area (Fig. 1) is located between the Australe and South Pole-Aitken basins, south of Tsiolkovsky crater on the southern lunar farside (centered at 40°S and 132°E). The largest craters inside our study area are Pauli and Roche craters in the east, Eötvös and Bolyai craters in the north, Van der Waals crater in the west, Carve crater in the south, and Rosseland crater in the center. According to the geological map of Wilhelms and El-Baz (1977), this region is dominated by craters and basin materials of Pre-Nectarian and Nectarian age. Van der Waals, Eötvös and Bolyai craters are the oldest craters with Pre-Nectarian ages, while Carve, Roche and Rosseland craters are thought to be Nectarian in age (Wilhelms and El-Baz, 1977). Pauli crater and some other smaller craters are the youngest craters, being Imbrian in age (Wilhelms and El-Baz, 1977). The most prominent mare basalts of our study area are located inside Pauli and Roche craters to the SW and Bolyai crater to the NW (Fig. 2). The geological map of Wilhelms and El-Baz (1977) also shows some smaller mare patches SE of Eötvös crater and west of Rosseland crater in the center of our study area (Fig. 2). According to Wilhelms and El-Baz (1977), all mare basalts in our study area are of Imbrian or Upper Imbrian age. They also mapped some light plains inside Roche, Van der Waals, Eötvös and Rosseland craters as being Imbrian or Nectarian in age. Performing CSFD measurements, Hiesinger et al. (2013) determined AMAs of the light plains inside Roche crater (3.91 Ga) and Eötvös crater (4.01 Ga).

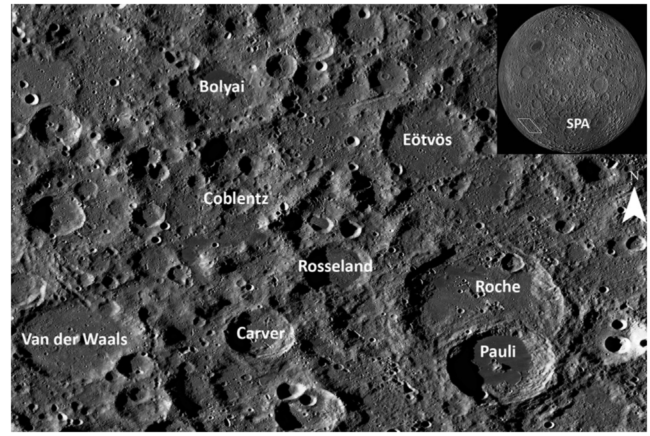

Fig. 1. Context image (WAC mosaic) of our study area. Crater names are labeled in white. The box in the upper right image shows the location of our study area on the lunar farside.

We selected this area to investigate the volcanic history of a relatively old area with a presumably thick crust. Models by Wieczorek et al. (2006) and Ishihara et al. (2009) both assumed crustal thicknesses in our study in excess of 50 km. However, new data from the Gravity Recovery and Interior Laboratory (GRAIL) mission show that the crustal thickness of the lunar farside is much thinner than previously thought (Wieczorek et al., 2013). Directly beneath our study area, Andrews-Hanna et al. (2013) identified a linear Bouguer gravity anomaly with a length of several hundreds of kilometers (Fig. 2). This feature has been interpreted as an ancient vertical tabular intrusion or dike formed by magmatism in combination with extension of the lithosphere (Andrews-Hanna et al., 2013). This possible dike might have stopped in the crust at 10–15 km below the surface, a depth that might also correspond to the maximum depth of impact brecciation and gardening, above which the density contrast would become less distinct (Andrews-Hanna et al., 2013). On the basis of the crustal thickness map of Wieczorek et al. (2013), we find that the crust beneath our study area is less than 30 km thick, which is similar to the thickness of the crust below the Oceanus Procellarum mare basalts.

Compared to the extensive mare basalt flows on the lunar nearside (e.g., Imbrium basin), the volcanic deposits in our study area