**LARGE SHIELD VOLCANOES ON THE MOON** Paul D. Spudis, Patrick J. McGovern, Walter S. Kiefer, Lunar and Planetary Institute, Houston TX 77058 spudis@lpi.usra.edu

Altimetry from LOLA reveals that almost all volcanic complexes in the lunar maria occur on topographic swells, 10-100s km in extent and several km high. We propose that these swells are shield volcanoes, equivalent to large basaltic shields found on Earth, Mars and Venus.

Although basaltic volcanism is a common process on the terrestrial planets, it manifests itself in differing styles and intensities on different bodies. Central vent, shield-building volcanism is common on Earth, Venus, and Mars; it may also have occurred on Mercury and Io. However, the lunar maria are flat, smooth plains, largely emplaced through flood eruptions. Small shields have been observed and mapped on the Moon for many years, but are typically less than a few km across and occur in clusters within selected areas of the maria. The Moon apparently lacks large shield volcanoes that typify some of the mountains of Earth, Mars and Venus [1-4]. Or does it?

Shield volcanoes have very low average slopes; the term was first coined to characterize broad, shield-shaped constructs on Earth made of low viscosity basaltic lava [5]. Pyroclastic activity is minor and mostly confined to late stages of eruption. Many (but not all) shield volcanoes display a summit crater (caldera) resulting from collapse over a drained or depleted magma chamber. Shield volcanoes typically display radial and circumferential fissure zones, which serve as pathways for magma to get to the surface. Cone- and dome-building often occurs near the summit of such features during the latter stages of shield growth.

LOLA global altimetry [6] reveals that although mare deposits are low-lying, several broad topographic highs are found in both eastern and western maria (Fig. 1). These swells are tens to hundreds of kilometers across and from 600 to over 3000 m high. We have identified seven major topographic swells (Table 1) in the near side maria. Interestingly, most of these swells correspond to high concentrations of small (km-scale) volcanic features as mapped over the entire near side by Guest and Murray [7]. This correspondence encompasses the familiar volcanic "complexes" Marius Hills, Rümker and Aristarchus, but also includes lesser known areas near Hortensius, Kepler, and Cauchy.

The largest of the newly detected features is eastern Mare Tranquillitatis, centered near the crater Cauchy (Table 1, Fig. 1). This area has long been known for small volcanic features, including cones, vents and sinuous rilles [7,8]. Topographic data reveal that the eastern part of Tranquillitatis is a shield almost 400 km across and over 2 km high. This broad shield has been the locus of multiple eruptive events between 3.6 and 3.8 Ga [9]. This shield may explain the apparent lack of topographic evidence for the putative Tranquillitatis basin [10], for which there is clear morphological evidence – Cauchy shield is built on the basin floor, creating a topographic high where a low is expected. Remote sensing indicates that basalt in the Cauchy region is only a few hundred meters thick [11], a fraction of the total relief. Superposed ejecta from the Serenitatis, Crisium, and Nectaris basins may contribute to topography in this region and low density ejecta may also contribute to the free-air gravity low. Nevertheless, the significant number of volcanic constructs at the top of the stratigraphic column and the shield-shaped morphology demonstrate the importance of volcanism in this region.

Both Marius and Rümker were long known to occupy topographic highs [7] and Apollo data demonstrated that Prinz-Harbinger is elevated and associated with part of the rim of the Imbrium basin [12]. Using Clementine altimetry, Spudis [13] suggested that the Marius Hills is a lunar shield volcano and Whitford-Stark and Head [14] suggested that most of the basalts of Oceanus Procellarum were erupted from a few volcanic centers. The T. Mayer-Hortensius area (Fig. 2) has been known as a volcanic center of small shields, rilles, and cones associated with the eruption of the famous late Imbrium flows [7]. This shield is similar to the Prinz-Harbinger shield in that it is built upon the main ring/rim of the Imbrium basin. Another shield (averaging 270 km in diameter) is superposed by the unrelated crater Kepler; although low (~ 0.6 km), this rise is big to be attributed solely to basin topography (Table 1). Unlike other shields, there is sparse evidence for volcanic vents or cones at the surface, although rough topography near the summit (partially obscured by Kepler ejecta) could be remnants of such activity.

The Aristarchus plateau seems to be a special case in which its topographic prominence is caused principally by structural uplifting associated with the formation of the Imbrium basin, only partly enhanced by eruptive activity. The highland block of the plateau shows clear structural control by Imbrium and basin ejecta is exposed in rugged terra there. However, massive eruption of lava both onto and away from the plateau is indicated by the presence of many large sinuous rilles [7], including Vallis Schröteri. These eruptions have partly re-surfaced the pre-existing plateau but ended before a significant shield-shaped construct could be finished. The present plateau is a shield in an arrested state of development whereas the Marius construct is a fully developed shield volcano.

The distribution of these shields is decidedly non-random. The largest group (Fig. 1) is found south and west of the Imbrium basin, within the large high-Th Procellarum province [15], while the largest shield (Cauchy) sits in the midst of a cluster of the Serenitatis, Nectaris, and Crisium basins. This pattern is likely caused by a stress-controlled mechanism for enhancing magma ascent in annular zones surrounding large basalt-filled impact basins [16,17].

The sizes and height-diameter ratios of lunar shield volcanoes are comparable to other large shields on Mars and Venus, particularly the low relief shields of the Alba Patera type [2-4; Fig. 3]. None of the lunar shields have summit calderas but many shields on Venus also lack summit craters but their presence is evident by eruptive landforms, radiating flows, and broad topographic swells. The absence of a caldera is consistent with mantle-to-surface magma transport in which dikes are aligned with regional (basin-loading) stresses [16,17]. Evidence for this is particularly strong at the Cauchy shield, which is topped by a set of large graben (Rimae Cauchy I and II) radial to Serenitatis basin.

The appreciation of lunar volcanic complexes as shield volcanoes does not alter our understanding of mare volcanism as dominated by sheets of flood lava erupted from linear fissures. However, we now believe that some significant fraction of erupted magma on the Moon has been emplaced via the mechanism of shield building. The ages of the mare surfaces associated with these features [9] range over a couple of hundred million years in the case of the Cauchy shield (3.4 to 3.7 Ga) to over 500 Ma for the T. Mayer-Hortensius shield (3.7 Ga to 3.2 Ga). Thus, shield building was active during the principal epoch of mare volcanism on the Moon.

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Table 1. Large shield volcanoes on the Moon

| "Shield" | Approx. summit | Diameter (km) | Height (km) | Comments |
|---|---|---|---|---|
| Marius | 14° N, 52° W | 330 | 3.2 | |
| Prinz-Harbinger | 26° N, 43° W | 166 | 1.6 | Built on highland block |
| T. Mayer-Hortensius | 13° N, 29° W | 300 | 2 | |
| Cauchy | 8° N, 35° E | 390 | 2.1 | |
| Rümker | 41° N, 59° W | 66 | 1.7 | Built on highland block |
| Aristarchus | 25.4° N, 50° W | 240 | 2.0 | Partly developed |
| Kepler | 8° N, 38° W | 270 | 0.6 | Very low slopes |

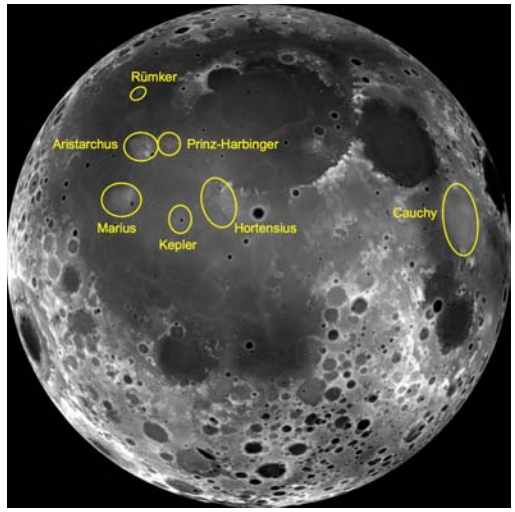


Fig. 1 Map showing location of large lunar shield volcanoes on LOLA topography [6]

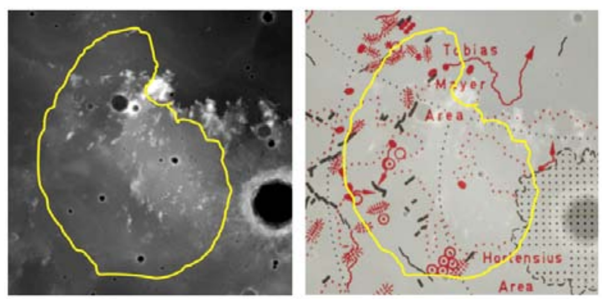


Fig. 2 T. Mayer-Hortensius dome, west of Copernicus. Approximate outline of shield in yellow. LOLA map on left; volcanic features map on right [7]

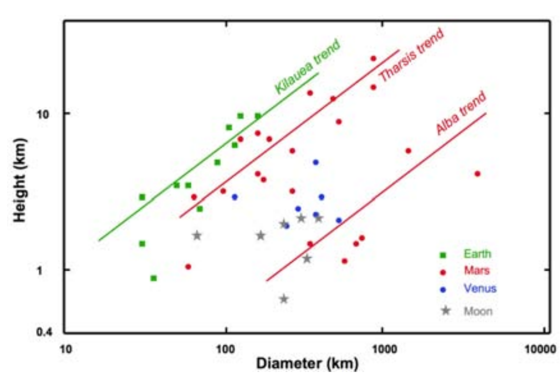


Fig. 3 Height-Diameter relations for shield volcanoes on several planets. The new lunar structures fall near low relief shields on Venus and Mars. Data for Earth [2], Mars [3] and Venus [4]; Moon – this study