COMPOUND FLOW FIELDS IN SOUTHWEST MARE IMBRIUM: GEOMORPHOLOGY, SOURCE REGIONS AND IMPLICATIONS FOR LUNAR BASIN FILLING. L. Qiao[1, 2], J. W. Head[2], L. Wilson[3], M. A. Kreslavsky[4] and L. Xiao[1], [1]Planet. Sci. Inst., China Univ. Geosci, Wuhan 430074, China, [2]Dep. Earth, Env. & Planet. Sci., Brown Univ., Providence, RI, 02906, USA, [3]Lancaster Env. Centre, Lancaster Univ., Lancaster LA1 4YQ, UK, [4]Earth & Planet. Sci., UC Santa Cruz, CA 95064, USA. Contact: le.qiao@cug.edu.cn.

Introduction: Recent advances in the analyses of the generation, ascent, intrusion and eruption of basaltic magma on the Moon [1-6] have provided an important context for the history of lunar mare volcanism and the nature of filling of the major impact basins. Here we review the implications of these treatments [3-5] for the nature and emplacement of effusive eruptions and use this framework to interpret the sequence of filling and styles of volcanism for the southwest quadrant of the Imbrium basin, known to contain some of the longest lava flows on the Moon [7-9].

Background: There are two causes of limits to lava flow length [3-5]: 1) In *supply-limited* or *volume-limited* flows (Fig. 1a), the supply of magma from the source region is exhausted before any cooling limitation can be reached. 2) In *cooling-limited* flows (Fig. 1b), the terminus of the flow cools sufficiently so that forward flow motion ceases; cooling-limited flows can often be recognized by the behavior of the more proximal parts of the flow where cooling has progressed to a lesser degree (Fig. 1b), and the continuing supply of magma to the flow can inflate the flow behind the cooled front and breach the thinner parts of the thermal boundary layer, forming breakout flows. Cooling-limited flow behavior is favored in lower-volume-flux eruptions, which optimize cooling time.

Effusive eruptions are modulated by effusion rate, eruption duration, cooling and supply limitation to flow length, and by pre-existing topography and have been classified [3-5] into four types: 1) Relatively *low effusion rate, cooling-limited flows* lead to small shield volcanoes; 2) *higher effusion rate, cooling-limited flows* lead to compound flow fields (CFF); 3) *even higher effusion rate, long-duration flows* lead to thermal erosion of the vent, effusion rate enhancement, and thermal erosion of the substrate to produce sinuous rilles; 4) *Extremely high effusion rate flows on slopes* lead to volume-limited flows with lengths of many hundreds of kilometers.

The Role of Cooling-Limited Flows and Compound Flow Fields in Mare Basins: Following dike emplacement and cooling of the marginal parts of the dike, effusion dominates over the widest part of the dike and centralizes flow; eruption rates can lie in the range from 10^4 to 10^6 m^3 s^{-1}[3-5] and eruptions that are in the lower part of this range, (~1-2 ´ 10^4 m^3 s^{-1}) are predicted to produce *cooling-limited* flows (Fig. 1b) commonly less than ~10-20 km wide, ~10 m thick and often up to ~200 km in length. Eruption durations are likely to be 2-3 weeks, and heat loss mechanisms cause cooling to penetrate into the flow interior, slowing its forward motion; when the Gratz number reaches ~300, the flow will stop advancing. At this point, lava is still being extruded from the vent and either causes inflation and breakouts in the flow levees toward the vent in the still-warmest part of the flow (Fig. 1b), or forms a new, often parallel, flow from the same vent. Each new flow emerging from the same eruptive phase will be emplaced in a similar cooling environment, and produce flows with similar aspect ratios. This process will repeat itself until the volume of magma in the eruption is exhausted.

The final result of the process is the production of a *compound flow field* (Figure 2), a series of cooling-limited flows whose general morphology will be related to preexisting topography and the thickness of succeeding flows. We have defined three types of compound flow fields: 1) *Linear-Parallel*: On a sloped surface, a compound flow field will often appear as a set of parallel flows of broadly similar lengths and widths. 2) *Linear-Braided*: On a sloped surface, succeeding parallel flows can be of different thicknesses and overlap with one another, producing a braided pattern. 3) *Knotted*: With decreasing slope and in relatively flat areas, succeeding flows and flow breakouts can meander and significantly overlap, producing a knotted appearance; in these cases, individual flow segments can only be traced for a few to several tens of km, and form complex patterns sometimes broadly radial to the vent area.

How many flows might constitute a compound flow field from a single eruptive phase? From theoretical considerations [3-5], the volume of magma predicted to represent a basaltic eruption on the Moon lies in the range of 100-1000 km^3. If a typical cooling-limited flow is ~15 km wide, ~20 m thick and ~200 km in length (~60 km^3), then these total volumes would imply that the number of cooling-limited flows in a compound flow field would be in the range of ~2-15.

Lunar compound flow fields have not been specifically reported in the literature but theoretical considerations [3-5] predict that they should be common. One reason for their lack of detection is that the extrusion of multiple parallel and overlapping flow lobes will produce a regionally relatively flat mare topographic surface that does not show the prominent lobate flow boundary scarps typical of the discrete and distinctive young Imbrium lava flows [7]. Secondly, following flow field emplacement, regolith formation processes will tend to average out and subdue any topographic variation remaining between adjacent flows. Finally, because compound flow fields by definition derive from the same batch of extruded magma, they are not expected to show any mineralogical or spectral reflectance variation; while they may or may not be different from a succeeding batch of magma, there is no reason to expect significant spectral differences that might reveal the presence of individual flows in a compound flow field.

Analysis of SW Mare Imbrium: New data from the LRO Lunar Orbiter Laser Altimeter (LOLA) instrument has provided insight into the presence and nature of lunar mare compound flow fields [10]. Detrended LOLA data have revealed the presence of compound flow fields in southwest Mare Imbrium (Figs. 3, 4) with typical flows in the range of 10-20 km wide and 100-200 km in length, implying volumes of up to ~50 km^3. Flow field morphology [3-5] illustrates well the role of preexisting topography in their emplacement. The three types of compound flow fields described above are seen (Fig. 3): In the central part of the basin, the oldest flows (Fig. 4) are *Knotted Compound Flow Fields*, likely representing emplacement in the flatter central regions. Along the SW basin margin, intermediate-aged phase B flows form *Linear-Braided Compound Flow Fields*, interpreted to represent formation on the increasing slopes caused by the loading and subsidence of the basin interior. Also along the SW margin, relatively young phase A flows form *Linear-Parallel Compound Flow Fields*, probably due to the increasing slope toward the interior with time. Note that the longest Phase B intermediate flows (up to 600 km long and up to 30-40 km wide in their distal reaches) are so extensive that they are interpreted to represent Type 4 eruptions, "*extremely high effusion rate flows on slopes* that lead to volume-limited flows with lengths of many hundreds of kilometers." Theory [3-5] predicts that for typical lunar eruptions, the number of cooling-limited flows in a compound flow field could be in the range of ~2-15: for the *Linear-Parallel* CFF, we find ~10 flows and for the *Braided-Parallel* CFF, about 13, in agreement with predictions.

The spatial distribution of flow margins seen in the detrended data enables us to trace the source regions of the CFFs back to the southwestern corner of Imbrium basin (Fig 3). The volcanic complex south of Euler crater proposed by Schaber [7] as the shared source region for all the young lava flows, however, is different compositionally, and stratigraphically older than the Imbrium lava flows. We find that Phase B is erupted from the Rima Euler source and the youngest lavas (Phase A) can be traced to linear fissures and cinder cones between crater Euler and Mons Vinogradov.

Conclusions: This SW Mare Imbrium example suggests that compound flow fields may represent a major new insight into the mode of formation and evolution of the lunar maria. Much of the lunar mare lava may have been emplaced in relatively low effusion rate, multiple cooling-limited flows (perhaps 10-20 in any one dike arrival event) producing previously unrecognized compound flow fields.

References: [1] Head & Wilson (1992) *G&CA* 56, 2155. [2] Shearer et al. (2006) *RMG* 60, 365. [3] Wilson & Head (2015) *Icarus*, in press. [4] Head & Wilson (2016) Icarus, in review. [5] Head & Wilson (2016) LPSC 47, #1189. [6] Jozwiak et al. (2015) *Icarus*, 248, 424. [7] Schaber (1973) *LSC IV*, 73. [8] Hiesinger et al. (2000) *JGR 105*, 29239. [9] Bugiolacchi & Guest (2008) *Icarus 197*, 1. [10] Kreslavsky et al. (2016) LPSC 47, #1331.

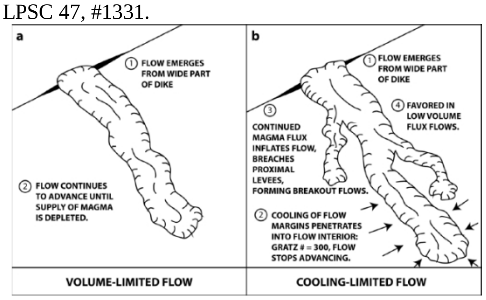

Fig. 1. Limits to lava flow length.

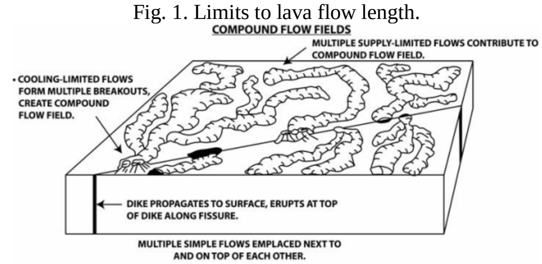

Fig. 2. Compound flow fields.

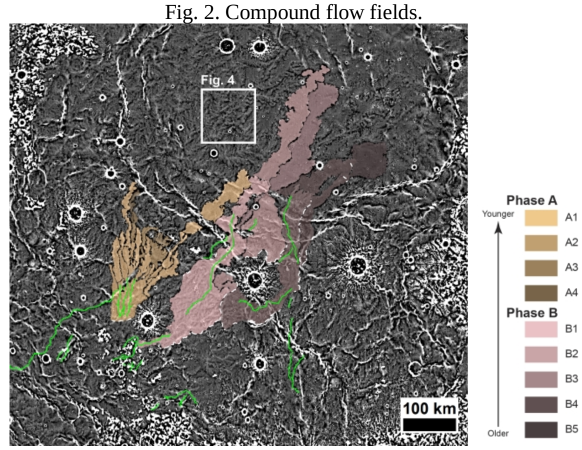

Fig. 3. Detrended LOLA altimetry map of lava flows within southwestern Mare Imbrium [11]. The green lines are lunar rilles, either linear or sinuous.

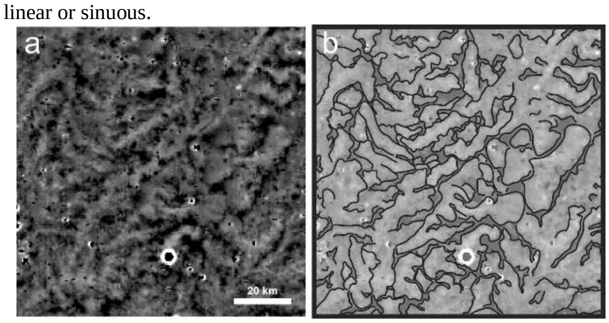

Fig. 4. (a) Detrended topography, (b) sketch map of example of Mare Imbrium compound lava flows. Location shown by box in Fig. 3.