Pyroclastic volcanism within lunar floor-fractured craters

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Rebecca J. Thomas, David A. Rothery, Susan J. Conway & Mahesh Anand

Department of Physical Sciences, The Open University, Milton Keynes, U.K. (rebecca.thomas@open.ac.uk)

1. Explosive volcanism in lunar impact craters

Localized lunar pyroclastic deposits (LPDs) commonly occur within **floor-fractured impact craters (FFCs)**, frequently at circumferential fractures near the crater wall [1,2]. It has been proposed that both floor-fracturing and crater-centered volcanism occur when ascending magma is arrested in the low-density zone beneath the impact crater [1,3] (Fig 1). A sill forms, which, on reaching the width of the brecciated zone, inflates to form a **laccolith**. Fractures form in the overlying crater floor materials, favoring magma ascent and effusive and/or explosive volcanism near the crater walls.

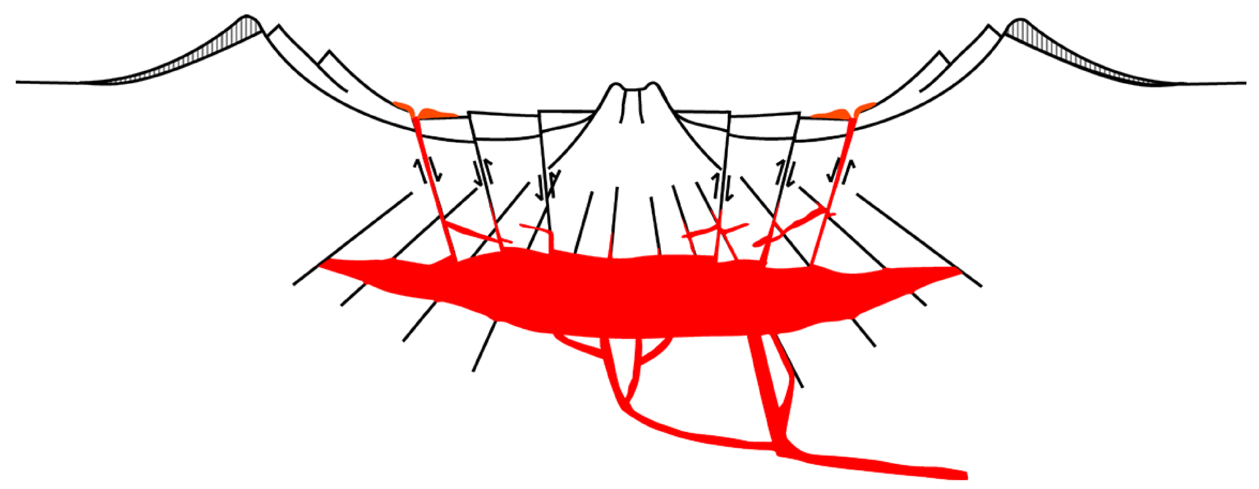


Fig. 1. Floor-fracturing and explosive volcanism caused by a sub-impact crater magmatic intrusion

2. The Problem

Explosive volcanism also occurs in impact craters on **Mercury,** but with **no associated fracturing or deformation of the crater floor** [4]. This suggests **deeper** magma storage on Mercury despite the higher gravity, which, if the depth of intrusion was governed only by buoyancy, would favor **shallower** intrusion and more crater floor fracturing than on the Moon.

Why was magma storage shallow enough to fracture the floors of lunar craters?

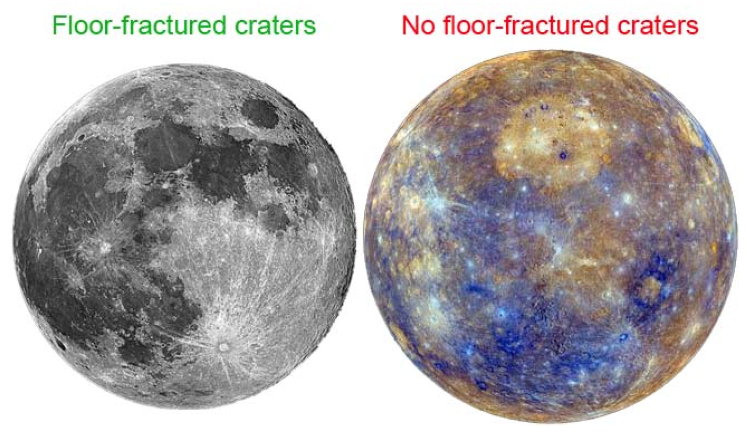


Fig. 2. The Moon (left) and Mercury (right)

It has been proposed [1,2] that the depth of intrusion beneath LPD-hosting craters was dictated by **magmastatic pressure**, because the intrusion was linked to a magma chamber responsible for **nearby coeval mare lavas** that were emplaced at a slightly lower elevation than the crater floor. This assumes, however, that:

a. Mare lava emplacement, FFC- and LPD-formation were coeval,

b. There was a linkage between dikes feeding the sub-crater intrusion and large-scale mare.

3. ...And our approach to solving it

We tested whether these assumptions are valid by taking a sample of FFCs and examining their association with large-scale mare lavas, in terms of stratigraphic age, proximity and elevation.

We also used crater morphometry to model [5] the magmatic driving pressure and intrusion depth capable of achieving the observed deformation in 15 FFCs with and 23 FFCs without associated pyroclastic deposits (Fig. 3) to test if these FFC types quantitatively differ.

1. Magma driving pressure spans a similar range in both sample sets: 4.7 - 141 bars.
2. The flexural thickness (Te) of the overburden above the modelled intrusion scales with crater diameter (R^2=0.86) in both samples, and is not statistically-separable between the two (Fig. 3).

Thus driving forces and intrusion depths of a similar magnitude can account for deformation in FFCs with and without LPDs, so we used both type to assess whether these can be attributed to magmastatic pressure.

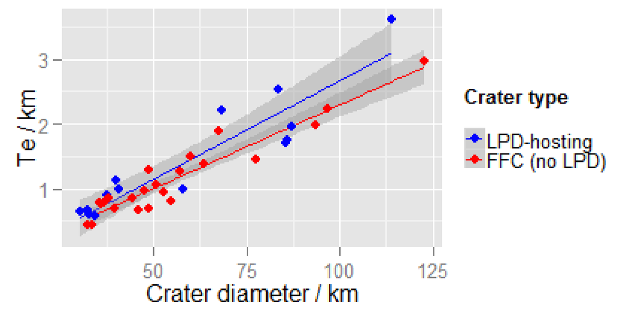


Fig. 3. Modelled Te in LPD and non-LPD-hosting FFCs (lines: linear fit, greyed regions: 95% confidence interval).

4. Can magmastatic pressure from nearby coeval mare lavas explain lunar FFC-formation?

Craters near a major mare and at higher elevation ✓

1. If the crater is adjacent to an extensive mare deposit, and
2. its floor is 0 - 500 m above the elevation of the mare surface,

then the existing model where FFCs form when magma stalls beneath impact craters at the level of nearby coeval mare deposits may be appropriate.

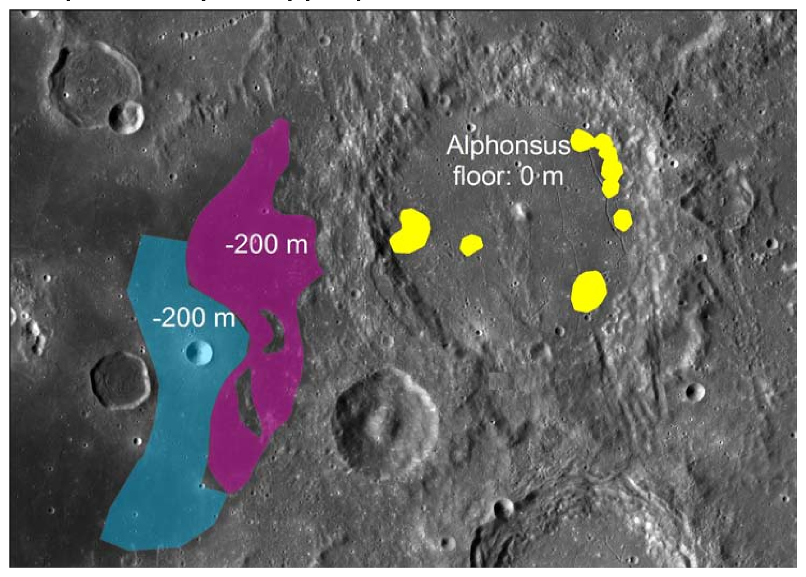


Fig. 4. LPD-hosting Alphonsus is directly adjacent to major Imbrian (blue) and Eratosthenian (purple) lavas, and at higher elevation

Craters post-dating mare ✗

If the crater superposes a surrounding extensive mare deposit, it must post-date it and the mare did not provide magmastatic pressure.

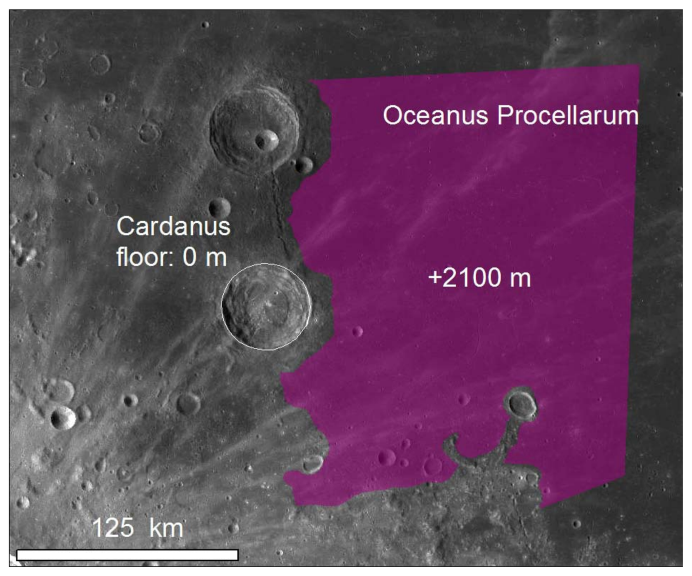


Figure 5. The FFC Cardanus (-72.6° E, 13.3° N) lies at the outer margin of Oceanus Procellarum, superposing the mare fill. The closest (Eratosthenian aged) mare deposit that may post-date it (sample in purple) is at a considerably higher elevation.

Craters at lower elevations than mare ✗

If the elevation of the crater floor is significantly lower than coeval mare, hydrostatic pressure should favor mare flooding of the crater rather than formation of a sub-crater intrusion.

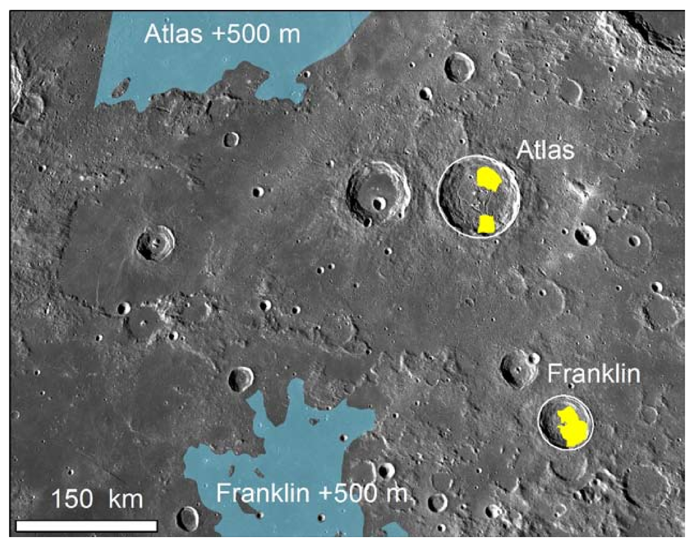
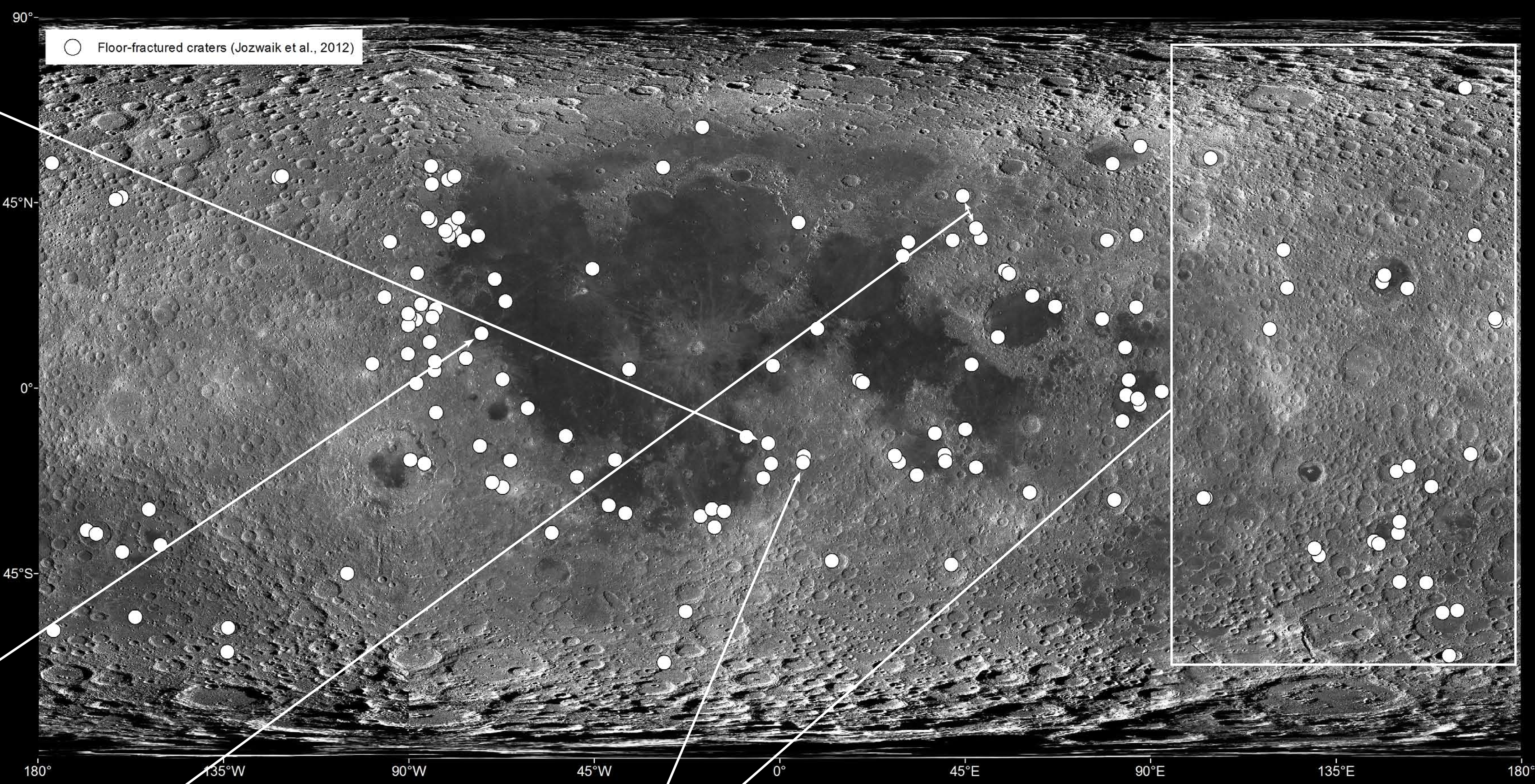


Fig. 6. The floors of LPD-hosting FFCs Atlas and Franklin are at lower elevations than the closest mare lavas (36.7° E, 44.4° N).



Craters remote from large-scale mare ✗

If the crater is remote (> 250 km) from extensive mare deposits it is improbable that its source is linked to a magma chamber responsible for mare emplacement, especially if its floor elevation is lower than the nearest such deposits.

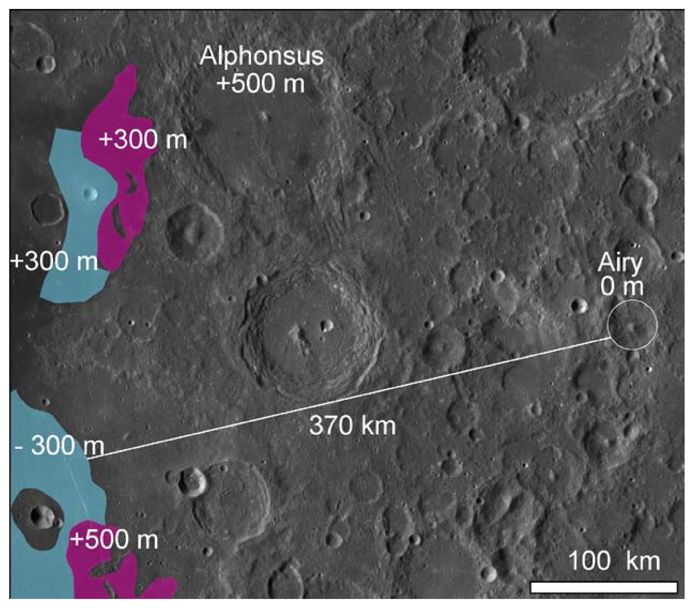


Fig. 7 While the LPD-hosting FFC Alphonsus lies adjacent to lavas that are at a slightly lower elevation than its floor, another LPD-hosting crater, Airy (5.8° E, 18.1° S) is ~ 370 km distant from the nearest lava that is at a lower elevation than the crater floor (Imbrian-aged mare samples: blue, Eratosthenian: purple).

5. Conclusion: Alternative mechanism - Extension

Where magmastatic pressure is a poor explanation for the formation of an FFC, **what other forces** could favor intrusions shallow enough to fracture the crater's floor?

- Along with driving pressure, the main control on intrusion depth is the **regional stress regime** [6,7]. Where there is compression, as on Mercury, deeper magma storage is favored, whereas in **extensional regimes, shallower intrusions** are favored.
- Modelling [8] suggests that loading by basin-filling mare deposits places the region in a broad **annulus around major lunar basins** in a state of extension (Fig. 8).
- Many FFCs that do not fit the magmastatic model **fall within this zone,** indicating that this stress regime may account, at least in part, for the formation of FFCs at such locations.
- On **Mars**, too, FFCs commonly occur in areas with a long history of extension [9], such as at basin margins and the north-south dichotomy boundary [10].
- Thus extension may favor FFC-formation on terrestrial bodies in general.

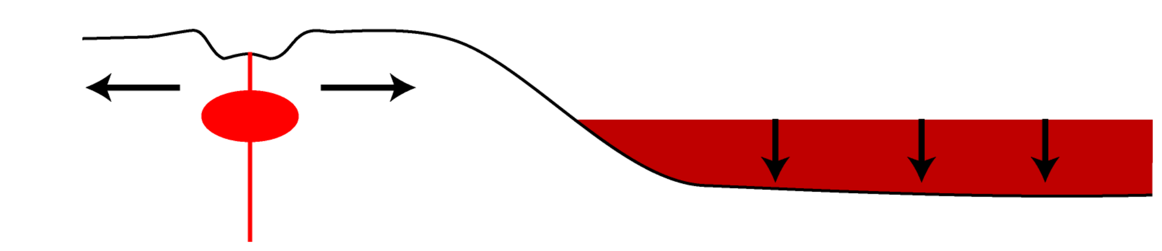


Fig. 8. Dense mare lavas put the basin margin area under extension, potentially favoring shallow intrusion beneath impact craters.

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