A FACIES MODEL FOR PRIMARY MAFIC VOLCANIC DEPOSITS.

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Introduction: Facies models are a key tool for inferring geologic processes from observations. They allow a trained geologist to examine a single outcrop and make pronouncements about (a) how the rocks were formed and (b) what types of rocks will be found at a similar stratigraphic level in other locations. Though facies models are well developed for sedimentary, metamorphic, volcaniclastic, and even felsic volcanic rocks [1-5], they have been generally neglected in the study of mafic volcanics. Since mafic volcanism is a pervasive process on the silicate planetary bodies in the Solar System, this lapse hits planetary science particularly strongly.

Facies models are simplifications of reality and exceptions are rampant when they are scrutinized. Issues are particularly common at the transitions between facies. As such, the adage that "all models are wrong, but some are useful" should be kept in mind. When used appropriately, facies models can be especially useful for establishing consilience (i.e., identifying the answer supported by the convergence of multiple independent lines of evidence). A common error is to use facies models to interpret small sets of extraordinary observations. The ability to discern what is "noise" versus the true underlying "signal" is essential for the successful use of facies models.

A Facies Model: The facies model presented here is aimed at determining the scale and vigor of a mafic eruption, especially in terms of duration and effusion rate. If one wishes to examine other aspects of a mafic volcanic deposit, a different model must be developed. In terms of eruption rate, essentially all eruptions have a relatively short waxing phase and then a longer waning phase [6]. This is the natural outcome from releasing fluid from a pressurized container (magma chamber) [6]. The facies model presented here focuses on features diagnostic of the evolution of the eruption.

This model divides the products of a mafic volcanic eruption into three sets of morphologic facies that correspond to their lateral distribution: (1) near-vent, (2) transport, and (3) flow front. Most eruptions will produce all three of these facies but only the first and last will always be present in effusive eruptions [and a purely explosive mafic eruption will only have the first [e.g., 2-3]. For this model, three descriptors (early-stage, middle-stage, and late-stage) are used to link the facies to specific eruption processes. Thus there are a total of 9 facies in the model presented below.

Early-stage near-vent facies. This facies is characterized by widespread pyroclastic fallout, ranging from ash to bomb size particles/clasts, arrayed around a fissure vent. Ash and lapilli can form a broad apron and spatter can build ramparts. Larger clasts are rarely preserved since they are able to agglutinate and produce rheomorphic lava flows. Such flows can drape topographic features near the fissure.

Middle-stage near-vent facies. At this stage, the eruption is focused around discrete points and cones of cinders/scoria often form. It is common for a distinct lava pond to form above the vent, especially if effusion dominates over explosive eruption of lava. Shelly pahoehoe is common.

Late-stage near-vent facies. Deposits associated with a very long-loved vent are limited because little primary pyroclastic material is produced and effusive lava efficiently enters the transport system. Instead, the edifice(s) around the vent area will start to suffer collapse. This is can be evidenced in mass wasting off of the cone or the formation of small pits around the vent. It can culminate in the syn-eruptive formation of a pit crater or caldera.

Early-stage transport facies. In the early stages of a lava flow, the fluid lava is carried in a broad sheet. Even if there is a solidified crust on top of the flow and/or the flow starts to become focused along some preferred pathways, the fluid interior is largely interconnected. Hummocky pahoehoe, rubbly pahoehoe, inflated sheets, and deflated sheet flows are some of surface textures associated with this facies.

Middle-stage transport facies. As the transport system matures, distinct channels and/or tubes form within the flow. Anastomosing is common and a more distributary planform is typical as the system transitions from early- to middle-stage.

Late-stage transport facies. Long-lived transport systems have a single well-established pathway. These channels and tubes also show various types of modification with sustained use. For example, lava tubes are often downcut and channels flow well below the levees established during peaks in discharge.

Early-stage flow front facies. The initial front for a lava flow is broad, essentially spanning the full width of the flow. The surface texture may be aa or pahoehoe but slabby pahoehoe is rarely found outside of this facies. If the flow terminates in this stage, it will be preserved as a "simple" flow.

Middle-stage flow front facies. A mature flow front has distinct lobes along which the advance is focused. These lobes are closely connected to the main pathways within the transport system. In this stage, aa flows are typically simple but pahoehoe flows can become compound.

Late-stage flow front facies. A long-lived flow front is characterized by secondary breakouts from within a stagnated lava flow. Blue-glassy, sharkskin, and spiny pahoehoe are some of the surface textures that are closely associated with this facies.

Discussion: Though simple, the, 9-facies model presented above sufficiently describes many of the key temporal and spatial relationships found within mafic lava flow fields [e.g., 7-8]. Deviations from the model predictions highlight anomalous situations that require special explanation. Such anomalies can be of great scientific interest or be inconsequential.

Temporal and spatial relationships. The choice of terminology indicates the expected temporal and spatial relationships of the facies. Some relationships are obviously not expected in this model. For example, the transport facies should not be more distal than the flow front facies. Similarly, a mature (late or middle-stage) transport facies should not be found associated with an early-stage near-vent facies.

Somewhat less obvious is the fact that few of the facies are expected to be stacked vertically with time. Only the middle-stage near-vent facies should overlie the early-stage near vent deposits, following the law of superposition in a straightforward manner. The flow front facies is often preserved on the top and bottom of the flow while the core preserves the later-formed transport facies. The temporal evolution of the transport facies is preserved across the width and length of a lava flow. The early-stage is recorded across most of the flow while the middle- and late-stage transport system makes up progressively less of the flow's cross section. Similarly, the most distal part of the transport system is expected to be less mature than the part nearest to the vent.

Length and time scales. The transition between these 9 facies has a typical length and time scale for a given eruption magnitude. For a typical Kilauea eruption, the transition from early to middle stage usually takes place in just hours to days in all three cases. The transition from the middle to late stage is more variable. Days to weeks is most common for flow fronts but months to years are typical for the vent and transport sections.

As indicated by other quantitative studies [e.g., 7-11], the balance between heat lost and heat carried by the influx of new lava appears to be the key to how these transitions scale with different eruptions. For example, due to their high heat influx and good insulation, the transport facies in most flood basalt flows did not evolve beyond the early-stage even after several years [12]. The observation that the transport system for the Athabasca Valles flood lava remains in the early stage even 300 km from the vent, despite having poor insulation, is evidence that the flux of hot lava must have been much higher than any known historical eruption on Earth [13].

Another example to consider is the observation that Hawaiian aa flows tend to have less division into small lobes and slower maturation of channels and tubes than pahoehoe flows. This could be explained as simply the result of the generally higher eruption rates for aa [14]. However, cooling is also retarded due to the release of copious latent heat [15]. Furthermore, the higher viscosity of the more crystalline interior of aa flows, which can be approximated with a yield strength [16], inhibits the formation of small toes. The facies model presented here cannot determine the relative effects of these processes but does provide a framework for further quantitative studies.

Interaction with water. This model requires modest modification if water-lava interaction is observed. In the vent area, external water can lead to far more explosive eruptions. The result is a higher proportion of pyroclastic materials and the development of features such as maars in middle-stage facies. If there is copious water, the cooling rate will be enhanced and the time and length scales will likely be compressed. Landforms such as tuyas and Moberg ridges are the result of a highly truncated transport facies connected to a flow front facies that includes a significant proportion of hyaloclastites. Fields of distributed rootless cones indicate sheet flow (early-stage transport facies) but cone alignments point to established lava pathways (middle-stage transport facies).

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