6. A much more dramatic demonstration can be done by snapping one of the stopcocks, and watching the tungsten oxide turn blue during the resultant explosion. However the heat generated by the hydrogen-oxygen reaction might be an interfering factor.
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Flowage Differentiation

Abstract. *Flowage differentiation is an experimentally demonstrable process capable of causing crystal and chemical fractionation in nature. It is a mechanism for forming olivine-rich rocks in a vertical or steeply dipping position without prior concentration on a flat floor. It explains the field observation that the chilled margin of a mafic intrusion may not be a representative sample of the average composition of the parent magma. In contrast to previous hypotheses of origin for composite dikes, it causes fractionation during and as a result of a single movement of magma rather than by multiple injections.*

The concept of flowage differentiation in the form described in this report is new to petrologic thought. In a flowing magma with solid and fluid phases, the solids can segregate to form mineral accumulates because of the inherent flow properties of the mixture. Segregation takes place away from the walls and toward the central axis of a conduit. The mechanism may be one of the processes which cause magmas to separate into diverse rock types and, in certain circumstances, may be more important than gravity, convection currents, or other processes in forming monomineralic concentrations. In addition to mechanical concentration of minerals, the process may produce chemical or cryptic zoning among the minerals themselves. Thus, early-formed olivine with a higher Mg/Fe ratio may be concentrated closer to the conduit axis than later-formed olivine with a lower Mg/Fe ratio. The feeder dike to the Muskox Intrusion which we describe here is a geological example. The picritic dikes of Skye (Bowen's "peridotite" dikes) recently described by Drever and Johnston (*1*) exhibit similar features. The process may also explain concentric zoning in ultramafic-gabbro intrusions.

The Muskox Intrusion is a Precambrian (1175 million years) layered ultramafic-mafic pluton situated in the Northwest Territories of Canada, crossing the Arctic Circle near 115°W longitude (*2*). It crops out for 74 miles (119 km) along a northwesterly trend. In cross-section the intrusion consists of a feeder dike connected to an overlying funnel-shaped body (Fig. 1). The latter part contains gently dipping layers of dunite, peridotite, pyroxenite, gabbro, and granophyre. In this report we discuss the feeder dike alone.

The feeder dike crops out for 37 miles, and ranges from 150 m to 550 m in width. It is nearly vertical and has sharply defined, chilled contacts with the surrounding Precambrian rocks (1765 million years and older). At its northern end it is connected to, and plunges under, the main body of the intrusion.

There are two types of rock, picrite (olivine-rich) and norite (olivine-poor, hypersthene gabbro), forming vertical zones parallel to the walls of the dike. Picrite may be considered as a norite plus 20 to 40 percent olivine. The margins of the dike are always formed of norite, while picrite is confined to the central third; picrite forms discontinuous lenses which are more continuous nearer the main body of the intrusion. In this latter area a third norite zone divides the medial picrite into two parts. Contacts between norite and picrite are sharp to transitional within a meter.

Mineralogical zoning in the dike has been described by Zwartkruis and Smith (*3*). The principal minerals are olivine (Fo_{59}-Fo_{78}), orthopyroxene (En_{67}-En_{82}), clinopyroxene ($Mg_{36}Fe_{24}Ca_{40}$-$Mg_{46}Fe_{14}Ca_{40}$), and plagioclase (An_{45}-An_{85}). The minerals indicate symmetrical zoning in the dike in the following ways. (i) Olivine increases in grain size, abundance, and Mg/Fe ratio from the dike margins toward the center. (ii) Plagioclase decreases in abundance, and increases in grain size, An-content, and degree of order from the margins toward the center. (iii) Pyroxenes increase in Mg/Fe toward the center.

There are three features of the dike indicative of its mode of origin. First, it is zoned parallel to vertical walls. Thus an origin by gravitative differentiation does not apply. Secondly, there are no chilled contacts between zones, only against the country rocks. Thus, an origin by successive injection of magmas of notably different age does not apply. Thirdly, there is a mineralogical symmetry to the rocks of the feeder which precludes random injection of separate norite and picrite magmas, even at high temperatures. The problem, then, is to explain how the first-crystallized, high-temperature minerals (such as olivine) in a magma can occur in the center of a vertical conduit, in the last part solidified completely, rather than along the conduit walls. In view of the inadequacy of current geological hypotheses, we devised experiments to test the possibility that the process responsible is analogous to flow phenomena observed in the transport of solid-fluid mixtures in certain industrial processes. Concentration of solid fractions toward

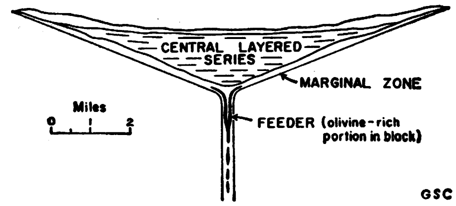

Fig. 1. Generalized section across Muskox Intrusion showing location of feeder dike and position of olivine-rich (picrite) zones within it.

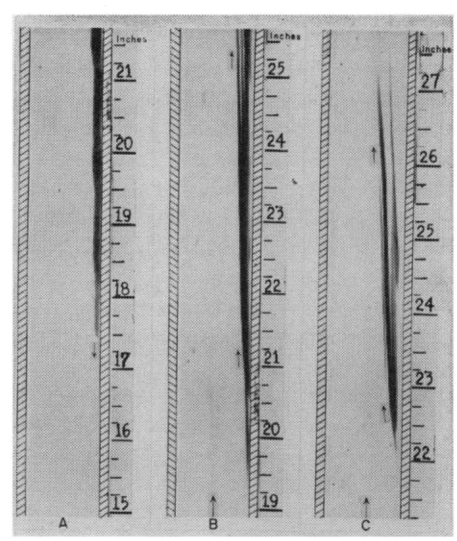

Fig. 2. Inward displacement of solid particles during vertical flow of fluid in a rectangular lucite conduit. The solid particles are Paraplex plastic, 0.053 to 0.037 mm in size, and the fluid is Shell motor oil SAE 20. Downward movement of solids in oil along margin of conduit is shown in *A*. Incipient inward displacement of solids as oil is forced up the conduit from below is shown in *B*. Continued migration of solids into central axis of conduit is shown in *C*. Average fluid velocity is 2 cm sec^{-1}.

the center of a pipeline or conduit has been described for pulp fibers in water by Forgacs *et al.*; Baines (*4*), blood corpuscles in capillaries by Poiseuille and many others (*5*); pumping coal slurry up vertical shafts by Condolios *et al.* (*6*). Baragar (*7*) has applied the concept of plug flow as observed in the transport of pulp fibers to explain the absence of plagioclase phenocrysts in the margins of certain sills in Labrador.

To study the process of flowage differentiation and its possible action during the movement of basaltic magma, scale models were developed in which solid-fluid mixtures were used. The fundamental units of measurement, mass, length, time, may be transformed into the properties of interest, namely length, density, viscosity, and velocity. These properties were scaled according to methods proposed by Hubbert (*8*). They were not amenable to absolute scaling since viscosity and velocity vary greatly in nature during intrusion. The scaled properties of the feeder dike are summarized in Table 1.

The dike width was the significant linear dimension and it was scaled directly to a convenient model size. A number of oils (Shell motor oil, SAE 10, 20, and 30; coconut oil; turpentine) can be used in such a model, and the choice of an oil fixes the density ratio scale. The important consideration in scaling density is to maintain the relative densities of solids and fluids in the model, so as to reproduce the conditions for crystal settling often observed in nature. Lucite, paraplex plastic, wood charcoal, and bakelite, in some instances dyed with different color pigments, can be used to simulate crystals of different density, size and shape. The particle size should be scaled by the same ratio as the dike width, but in practice this produces an inconveniently small size. In our experiments, powders were ground to −270 to −400 mesh and the resultant scale ratio is given in Table 1.

Hubbert (*8*) pointed out that, for a geometrically similar fluid model, dynamic similarity is ensured when the Reynold's number of the model and the original body are the same. Since the length and density ratios had been selected, the viscosity and velocity ratios had to be related according to

$$\frac{\text{Reynold's No. of model}}{\text{Reynold's No. of original}} = 1 = \frac{L \times D \times v}{V}$$

Table 1. Properties of the Muskox feeder dike and scale model.

Muskox feeder dike	Experimental model	Model ratio
	Width or diameter (average)	
700 ft (2.13×10^4 cm)	2.54 cm	1.2×10^{-4}
	Density of magma	
2.65	0.899 (Motor oil) (SAE 20)	0.335
	Density of the crystals or solids	
3.50 (Fo_{75})	1.175 (Red Lucite)	
3.52 (Fo_{70-71})	1.180 (Red Lucite)	
3.58 (Fo_{67-68})	1.200 (Paraplex plastic)	0.335
	Size	
1.5 mm (olivine)	≤ 0.037 mm to 0.053 mm	≤ 2.46 to 3.53×10^{-2}
	Shape	
Round or oval	Round or oval	
	Dynamic viscosity (poises)	
3×10^3 to 4.35×10^2	1.470(25°C) to 0.213(65°C)	0.49×10^{-3}
	Velocity	
≈ 3 to 15 m hr^{-1}	1 to 5 cm sec^{-1}	12.189
	Reynold's No.	
Same as model	1.5 to 53 (oil) 10^{-3} to 10^{-2} (particles)	1

where L is the length ratio, D the density ratio, v the velocity ratio, and V the viscosity ratio; or,

$$\begin{aligned} V &= 1.2 \times 10^{-4} \times 0.335 \times v \\ &= 0.402 \times 10^{-4} \times v. \end{aligned}$$

The viscosity of oils used in various experiments was measured at different temperatures by the standard A.S.T.M. (*9*) method. The corresponding magma viscosity may have a wide range of values during movement from the mantle to the earth's surface. MacDonald (*10*) reports that the viscosity of Hawaiian basaltic lavas near hot volcanic vents is 2 to 4 × 10^3 poises, averaging 3 × 10^3 poises. Hence, in one quasi-scale model (Table 1) a viscosity scaling ratio of 0.49 × 10^{-3} is obtained by assuming that a model viscosity (1.47 poises) corresponds to a magma viscosity of 3 × 10^3 poises. The measured model viscosities were made on oil without solids; addition of solids in the model increases the viscosity of the mixture. The viscosity scaling factor can be considered only in terms of orders of magnitude rather than absolute values.

The choice of viscosity ratio fixes the velocity ratio as 12.189, according to the restrictions of equality of Reynold's number cited previously. Thus a model velocity of 1 cm sec^{-1} will correspond to a magma velocity of approximately 3 m/hour. This value cannot be considered definitive, since magma velocities may range from very low values to several kilometers per hour. In the model it was observed that segregation effects were obtained over a wide range of velocities, from those necessary to overcome crystal settling to those which produce turbulence.

The velocities used in the model exceeded the settling velocities of particles and were directed in a vertical direction. Thus the effect of gravity could be ignored and the dimensional model could be considered a special case (*8*) in which time was an independent variable. The velocity-gradient profiles indicated that the flow characteristic was laminar. The fluid behavior is Newtonian; however, at high concentrations the solid-fluid mixtures are non-Newtonian.

Models were constructed in which both tubing and parallel plates made of lucite plastic were used. The parallel plate apparatus and tubing had inner walls 2.54 cm apart. Water jackets were used to control the temperature and observe the influence of changes in viscosity. The flowage of solid-fluid mixtures was in a vertical direction, propelled by a hand-operated piston.

Experiments were conducted under various conditions of shear gradients, different sizes, shapes, density, and concentrations of particles being used. In early experiments the process of segregation of solid and fluid particles in a vertical conduit under various conditions of laminar flow and settling was studied. Later, geometrically similar structures were simulated and the flow of mixtures was studied under conditions of changing lateral and vertical thermal gradients, pinching and swelling of the conduit, obstructions in the path of flow, turbulence, and pulsating conditions of flowage. The pertinent observations we made may be summarized as follows.

1) In laminar flow the solid particles separate from the walls and gradually increase in concentration toward the center, as solid-fluid mixtures are pushed upward in the conduit (Fig. 2, *B* and *C*).

2) Spherical and rod-shaped particles rotate as they move from the walls toward the center.

3) The rate of concentration toward the center increases with increased velocity or shear gradient. Thus constrictions in the conduit accelerate the process.

4) For equivalent shapes, the rate of inward movement of solids increases with the particle size. Similar observations on the effect of particle size in suspensions have been made by Vand (*11*), Maude and Whitmore (*12*), and Karnis *et al.* (*13*).

5) Pulsating flow conditions may cause the central filament of particles to break up (Fig. 3*C*). (This will occur when gravity or thermal convection forces exceed the flow velocity.) Increased rate of flow will again cause a central filament to form (Fig. 3*D*).

A rearrangement of particles in the parabolic field of flow has been noted by a number of observers. Starkey (*14*) observed the concentration of rigid particles in the central region of a tube during flow of an originally homogeneous fluid mixture containing suspended solids, and proposed a theory to explain his observations. Vejlens (*15*) observed that a rigid sphere released near the wall moved away from the wall and that this effect increased rapidly with increased particle size. Karnis *et al.* (*13*) found that rigid particles with very low Reynold's number ($< 10^{-6}$) moved near the tube center in viscoelastic fluids.

The mechanical principles of segregation of solid particles are not thoroughly understood. The wall effect (*11, 12*) due to the mechanical interactions of particles and rigid walls, the Magnus effect (*16*) arising from a combination of rotatory and translatory motion of a particle relative to the undisturbed flow of the fluid, and the criterion of minimum energy dissipation (*17*) are considered the best explanations of particle segregation from the walls and movement toward the center. If the formalism of the Magnus effect is adopted it can be shown that a lateral force is developed on the particles, directed inward toward the central axis of the conduit; this centripetal lateral force can be calculated from the Kutta-Joukowski formula (*16, 18*).

In general, the forces acting on solid particles participative in the flow of an inhomogeneous fluid consist of three components: a component due to differential translatory motion of adjacent parts of the fluid phase; a component due to differential translatory motion of solids relative to fluid; and a component due to rotation of the solid particles. The effect of the second component is small compared with the other two, except at fairly high concentration (*14*). In the flow mechanism under consideration, then, translation of the fluid takes place together with the simultaneous translation and rotation of the solid particles within it. It can be shown (*19*) that a spherical particle carried along in a nonuniform velocity gradient is subjected to a shear couple and a longitudinal force acting in the direction of streaming. This causes rotation in addition to translation along the direction of flow (Fig. 4). It is these components of translation, acting in conjunction with the rotation, that give rise to lateral components of translation. The existence of a lateral component of translation normal to the flow direction leads to the conclusion that when a solid-fluid mixture flows through a conduit (that is, when magma carrying suspended or settling crystals flows through a fracture) there will be a continuous motion of solids toward the center. As the concentration of particles increases a column of solids with immobilized fluid develops. The mean free path in the flowing fluid increases and the concen-

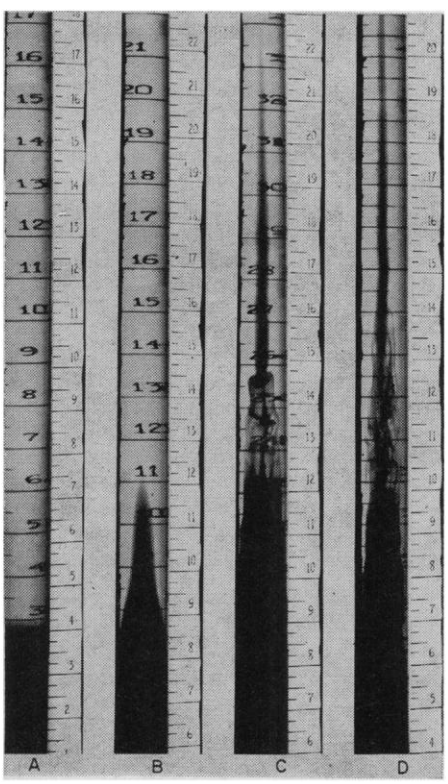

Fig. 3. Concentration of solid particles along axis of vertical tube during flow. Column *A* represents the start of the experiment; solids are settling toward the piston at the bottom of the tube; *B* shows the central filament as the mixture moves up the tube at initial average velocity of 2 mm sec^{-1}; in *C*, the experiment has been stopped for 2 minutes and the filament is breaking up due to settling; *D* shows renewed convergence of the filament as the mixture moves up tube at an average rate of 5 mm sec^{-1}.

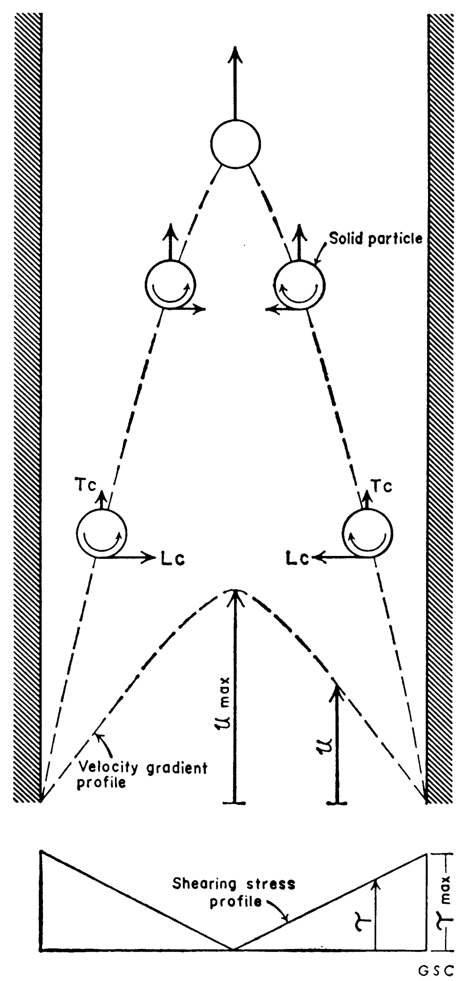

Fig. 4. Schematic diagram showing the nature of forces acting on solid particles in laminar flow of a fluid at variable rates of shear. T_c, longitudinal force component; L_c, lateral force component; τ, shearing stress component; *U*, velocity component.

tration process is further facilitated.

It has been demonstrated in the field that a segregation of early-formed olivine crystals occurs in the center of the Muskox dike, and by studying the model we have found that this is an expected condition during flowage of a solid-fluid mixture. The geological significance of the process remains to be explained.

In the simple case of the Muskox dike, flowage adequately explains both the concentration of olivine toward the center and its cryptic zoning (the rise of Mg/Fe ratio in olivine toward the center). At the time of intrusion, the first olivines with the highest Mg/Fe ratio started to crystallize. As the magma flowed and cooled these crystals migrated away from the walls, leaving the residual fluid depleted in Mg relative to Fe. Succeeding crystals became relatively more rich in iron as the process proceeded. The chemical evolution is similar in principle to that occurring during normal gravitative crystallization, except that separation of crystals occurs across the gravity field rather than vertically within it. Thus the process may be considered as the flow analogue of gravitative differentiation.

The chemical or cryptic zoning of minerals by flowage differentiation is best developed among the first formed crystals and becomes more complex as crystallization proceeds. In the Muskox dike, both orthopyroxene and plagioclase show cryptic zoning which can be interpreted as being due to flowage. However their rims show zoning due to chemical reaction with interstitial liquid and this tends to mask the earlier zoning due to flowage. Final crystallization of the interstitial liquids produces mineral compositions related to the local site of crystallization rather than to the dike as a whole.

Where double, parallel, olivine-rich (picrite) zones occur in the center of the dike, several explanations are possible. Obstructions in the conduit, sudden swelling, turbulence, or pulsating conditions of flowage will cause the simple flow pattern to break into several parts. However, in general these effects will only modify the shape of the central mass of crystals by breaking or bending it, but will not destroy it completely.

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Dome-Shaped Volcanic Gas Vents in Arizona

Abstract. *Dome-shaped fossil gas vents on one of the Hopi Butte diatremes attest to escape of gas during the closing stage of volcanic activity.*

Dome-shaped fossil gas vents occur on top of one of the Hopi Buttes, the Dilkon diatreme, 3.2 km (2 miles) west and 1.6 km north of Dilkon Trading Post. Late Pliocene volcanic activity formed the Hopi Butte diatremes, and the mafic lava is monchiquite (an igneous rock composed of olivine, pyroxene, and mica in a matrix of analcime).

The Dilkon diatreme is 90 to 120 m (300 to 400 feet) high, is roughly circular and has a diameter of approximately 0.4 km at the top. The butte is largely made up of monchiquite which toward the top grades into a rock composed of well-rounded balls of monchiquite ranging in size from a few centimeters to 0.6 m in diameter, in a matrix of agglomerate (accumulations of volcanic eject). Capping the butte is about 3 m of thinly layered tan limestone which was deposited in a shallow lake within the diatreme. Around the edges of the diatreme the limestone dips inward 15 to 20 degrees, indicating postdepositional sinking or collapse of the central volcanic vent; the fossil gas vents (Fig. 1) are found in the limestone and cover most of the upper surface of the butte.

The dome-shaped fossil vents were formed by vertically rising gas that quietly escaped from below. The dome shape generally persists downward into the underlying limestone layers and only locally was turbulence sufficient to destroy completely the thin bedding of the then still-unconsolidated limestone. Vesicular channelways that carried the rising gases lie within the dome-shaped structures and the limestone immediately below (Fig. 2).

Both thin sections and slabs cut through the domes were examined microscopically for organic material; none was observed. After solution of the limestone in acid, the residue (about 10 percent of sample) was analyzed

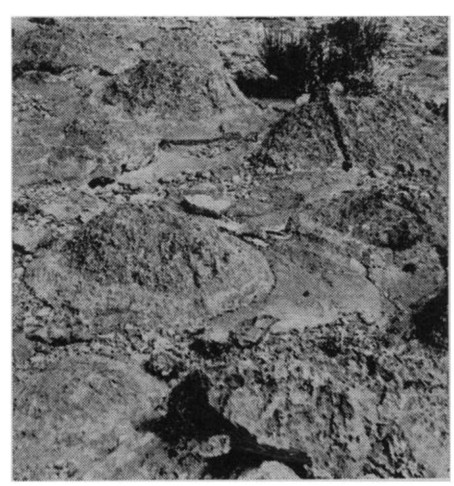

Fig. 1. Fossil dome-shaped volcanic gas vent domes on exposed surface of diatreme.