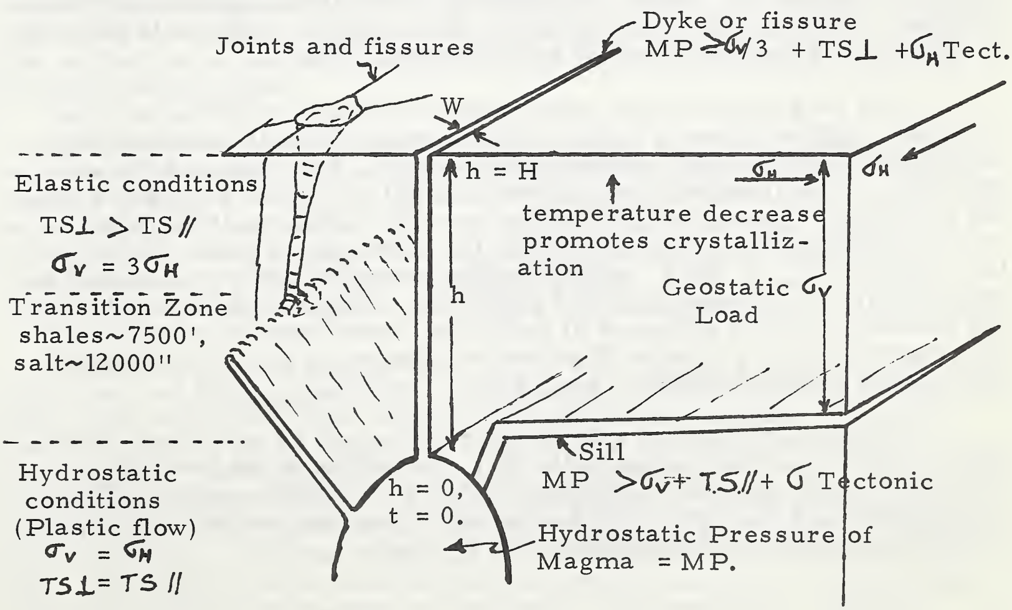
# CRUSTAL CONTROL ON THE EMPLACEMENT OF KIMBERLITES

David P. Gold, Department of Geosciences, The Pennsylvania State University, University Park, Pa. 16802

Although much is known about the composition and distribution of intrusive rocks, relatively little is known about their mechanism of intrusion. The latter has been hampered by (a) a purely descriptive terminology that does not relate to intrusion conditions e.g., for dykes (discordant) and sills (concordant) with respect to the layering in the country rocks, (b) the paucity of data on stress distribution and magnitude of the near surface rocks and (c) only speculative inferences on stress states under the deep-crustal or subcrustal conditions. Likewise hypothetical emplacement mechanism include passive injection into openings and intrusion according to laws of hydrostatics (Gilbert, 1887), injection from "telluric pressure" (Spurr, 1923), magmatic stoping (Daly, 1903), a salt-dome type mechanism by differential geostatic loading (Gussow, 1962) and a gas-solid erosion and entrainment process (fluidization) (Cloos, 1941; Reynolds, 1954). All the postulated mechanism require an unbalanced hydrostatic condition regardless of the method of achieving it (tension, compression, differential loading, heat, crystallization, outgassing).

The emplacement of kimberlites as funnel shaped pipes, irregular fissures and dykes, and as sills indicates a structural control in the near surface environment of the ascending kimberlite magma and the volatile phases that might be outgassed during crystallization. The

Figure 1. Schematic view of dykes, fissures, pipe and sill and their controlling parameters



emplacement mechanisms are linked to magma pressure, saturated vapour pressure, elastic limit and yield strength of the host rock perpendicular and parallel to bedding, and the horizontal and vertical stresses prevailing in these rocks. Also emplacement time should be equal to or less than crystallization time, especially in thin dykes. In addition the laminar flow transport distance of magma in a conduit is dependent on the geometry, specifically the width W and depth H, and has been expressed mathmatically by Szekely and Reitan (1971) as

$$\frac{dh}{dt} = \frac{W^2(\sigma_v - \rho gh)}{12\mu(h)\, h}$$ where h = 0 at time t = 0 (see Fig. 1) and

$\mu(h)$ is the position dependent viscosity defined by the Hagen-Poiseuille equation

$$\mu_{(h)} = \mu_o e^{kh},$$ where $\mu_o$ = viscosity at h = 0.

For latent heats of fusion of the order of 150 cals/gm, they show that dykes from magma sources greater than 30 km deep would have conduit widths greater than 12 m, which decreases asymtotically to about 1.5 m wide at 15 km focal depth. Only by fissure propogation from the magma interface to the free surface, with the entrainment of solid particles in a gaseous medium, could thinner conduits be emplaced from such depths. Also the mass transport would be directly proportional to differential pressure and indirectly proportional to friction between particles and with the walls.

Assuming ideal conditions of near surface rocks below their elastic limit and free of any tectonic stress, then the horizontal stress ($\sigma_h$) should be equal to approximately 1/3 of the vertical load ($\sigma_v$). Hydrostatic condition should prevail ($\sigma_v = \sigma_h$) at greater depths, corresponding to stress states above the elastic limit or yield strength of crustal rocks (about 90 $K_g/cm^2$). The threshold between elastic and ductile behaviour for shales corresponds generally to depths of 3000 to 7500 feet (Mudge, 1968), and requires depths of the order of 12000 feet to overcome the elastic limit of salt (Gussow, 1962).

The lack of extrusive, and volumetric rarity of intrusive kimberlites, implies either a rarity of these events or that relatively little magma reaches the near surface environment. For dyke and fissure (see Fig. 1) development magma pressure (M.P.) must be greater than the horizontal stress plus the tensile strength of the overlying layered rocks perpendicular to bedding (T.S. $\underline{1}$). For near surface conditions M.P. $\geq 1/3\ \sigma_v$ + TS $\underline{1}$, which implies intrusion pressures less than the overburden or lithostatic load pressure. These conditions favoring tension, must be enhanced at depths by superimposed crustal and subcrustal tension (tectonic) if dykes and fissures are to form under hydrostatic stress conditions i.e. MP $_v$ + ($-\sigma_{Tectonic}$).

The development of sills would be favoured by conditions (see Fig. 1) where magma pressure (M.P.) Superincumbent load ($\sigma_v$) + tensile strength parallel to bedding (T.S. $/\!/$); condition unlikely to prevail at depth greater than 7500 feet unless there are anomalously high superimposed horizontal compressive stresses.

Assuming the kimberlite source is deep (60 - 340 km) then a rapid gas streaming process is mandatory to explain (a) the disequilibrium mineral assemblages in kimberlite breccias, (b) the extreme stratigraphic mixing of inclusions and (c) the paucity of metamorphism of these inclusions, and (d) anomalous width to depth ratio of kimberlite dykes and fissures. The high diffusivity of gas, (e.g., underground nuclear explosions suggest that the precurser gas has little drilling power), and the excessive demand on a low heat carrying capacity gas to fracture, brecciate, erode, and heat the host rock requires that it move upward in essentially open fractures, otherwise frictional factors on particles and the walls would be sufficiently large to shut off the system. Notwithstanding an open fracture, which could not exist for long at these depths of high plastic flow, the entrained xenolith require a large volume of gas for mass transport, a steep pressure gradient at the base of the fissures, and particle acceleration to near sonic velocities. Szekely and Reitan (1971) calculated that 40 $cm^3$ of $H_2O$ would be evolved per $cm^3$ of magma of density 2.8 gm/cc containing 1% $H_2O$ and a temperature drop from 1200 to 400°C due to adiabatic expansion over a pressure gradient of 8 kb (8 $cm^3$ vapor would be evolved from a 0.2% $H_2O$ magma.

Moreover the travel time for water vapor at 1000° and 500°C respectively from a 30-km deep fissure would be 34 and 41 seconds, compatible with the requirement of a short duration for the fissure opening stage. This does not imply a unique event in time or space; intrusions would take place as long as the source material was not depleted and conditions of tectonic tension prevailed. In fact for a regime of regional tension, multiple fissuring would be expected.

Although most pipes are irregular fissures and may extend to great depth, the cylindrical and funnel shaped pipes are essentially near surface features controlled by intersecting fissures and joint systems, and in place may originate from a sill (Francis, 1967). Moreover, kimberlite intrusions must originate in deep-seated tension fractures, which are unlikely to occur in a uniaxial stress field, a necessary condition for pipe development.

Alternatively a rising volatile-rich magma with no gas phase would become saturated at lesser depth and exsolve a gaseous phase with a marked pressure increase, (Morey 1922) perhaps sufficient to cause upward migrating fractures. Any release of pressure would enhance crystallization and promote additional outgassing with entrainment of both magma and wall rocks in the gas stream. This process would enable sills to form whose assemblages were essentually in equilbrium.

Monticellite-mica peridotites, sills, and diatreme breccia pipes, fissures, and dykes of alnoitic, carbonatitic, and kimberlitic materials occur in a restricted area west of Montreal area, Canada. The sills contain megacrysts of augite and olivine, and xenoliths of websterite, harzburgite, dunite, peridotite and rare lherzolites in a coarse grained poikilitic textured matrix. The matrix consists of phlogopite, monticellite, forsterite, titansalite, melilite with accessory apatite, magnetite, perovskite, calcite, scapolite and secondary carbonates and zeolite. Phlogopite and/or monticellite oikocrysts are up to 1 cm across, commonly contain inclusions of forsterite and magnetite. Locally, monticellite and melilite are intergrown. The regional association with diatreme pipes and the high temperature moderate to low pressure mineral assemblage suggest the sill is an "equilibrated kimberlite".

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