like a plug—very much like toothpaste being squeezed out of a tube.

In summary, the first essential for intrusion to result is that there must be a plastic medium (salt, mud or clay, ice, magma) and this must occur in the form of extensive sheets. In the case of salt, before buoyancy can begin to play any role, it must be buried at a depth of from 2,000 to 5,000 ft. Salt starts to become plastic below 12,000 ft. on account of pressure, and at about 25,000 ft. it becomes mobile on account of temperature. When it is mobile, it behaves hydrostatically and, as the surface load is never in exact balance, it will move laterally to places of less overburden pressure, where piercement or doming occurs. This state of balance is extremely delicate. Once initiated, flow would continue until the supply is exhausted.

The second requirement, then, is that there must be an imbalance in geostatic load distribution to initiate horizontal hydrodynamic flow. This lateral flow can only be due to geostatic load, but once piercement occurs, geostatic load plus the ever-increasing effect of buoyancy will cause the intrusive mass to rise rapidly through the overlying strata. Buoyancy only becomes a powerful force as the height of the intrusion increases to large proportions. At first, when no vertical relief exists on top of the evaporite layer, buoyancy is zero and piercement of the overlying strata cannot be caused by buoyancy alone. In the case of salt, buoyancy is known to be positive, but for magmas, it may be positive (up) or negative (down), depending on the density difference. Accordingly, buoyancy is not a requirement for intrusion, but is a modifying effect. Thus, intrusion of a very dense magma, such as kimberlite, can also occur.

As the salt moves into shallower overburden depths with their reduced geostatic load and lower near-surface compaction, the diameter of the stock generally increases. When the hydrostatic pressure of the salt (or magma) column balances the geostatic overburden pressure of the rock column on the source reservoir, or when the supply is exhausted, upward movement will cease. Thus, heavy basaltic magmas and even salt domes frequently do not reach the surface. It is postulated that the intrusive salt or magma should spurt into joints or fractures in the overlying rocks, speedily rising toward the surface, slowing down on reaching shallower depths (of less than 5,000 ft. in the case of salt), so that gentle flow may occur at the surface. Where the salt has reached the surface, it can flow out on the surface, or downhill like a glacier at the time of extrusion, but once it cools, it can only move downhill by very slow solid creep. This is in no way a measure of the rate of intrusion.

It should be pointed out that isopach thinning of a formation over a dome is not evidence of uplift during sedimentation unless erosional thinning can be demonstrated: thinning can also occur by stretching or by compaction of the strata above a dome at the time of intrusion.

In conclusion, heat is extremely critical for salt intrusion to result, and the energy driving the motion is gravitational potential energy derived primarily from the weight of the overburden, or geostatic load, and supplemented by the buoyancy effect caused by a density differential.

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Olivine Nodules in a Phonolite of the East Otago Alkaline Province, New Zealand

NUMEROUS olivine nodules were recently reported by Sang Lyen[1] in a cossyrite phonolite flow from one of the lesser centres peripheral to the Dunedin Volcanic Complex, of Upper Miocene to Lower Pliocene age. The nodules are " . . . of varying size, widely scattered in the flow. Small nodules, a fraction of an inch across, may be found distributed widely, while larger types are mainly concentrated in the medial layers of the flow. . . ." Blocks up to 20 in. long were found.

The nodules are similar in appearance to those frequently found in basic lavas of alkaline affinities[2,3] and have similar mineralogy: olivine ($\beta = 1{\cdot}672 \pm 0{\cdot}002$), optically neutral, often with undulose extinction in wide sub-parallel bands; clinopyroxene ($\beta = 1{\cdot}685 \pm 0{\cdot}002$), $2V = 58°$ (ref. 1), bright green in hand specimen, with occasional exsolution lamellae of orthopyroxene; orthopyroxene ($\beta = 1{\cdot}672 \pm 0{\cdot}002$), very high negative $2V$; spinel ($n = 1{\cdot}80 \pm 0{\cdot}005$ (in O.U. 17738) and $1{\cdot}83 \pm 0{\cdot}01$ (in O.U. 17737)), brown interstitial grains, sometimes with narrow reaction rims against silicate.

The volume of exposed trachytes, phonolites, and salic pyroclastics accounts for about a quarter of the Dunedin Complex as a whole, while types intermediate between these and the basalts and basanites represent less than 5 per cent. On the other hand, trachytic lavas and pyroclastics made up almost all the initial eruptive phase of the main volcano, and over half the lavas of the third main eruptive phase were phonolite (estimates derived from incomplete computations by the late Prof. W. N. Benson).

In many continental alkaline provinces (such as East Africa) the overall volume of salic lavas and pyroclastics equals or exceeds that of associated basic eruptives, while flows of intermediate composition are but sparsely represented, as they are in the Dunedin Complex. Implicit in some recent work on the subject[4–7] is the idea that in such regions a mechanism other than fractional crystallization is required to account for the disproportionate amounts of basic, intermediate and salic lavas.

Olivine nodules in alkaline basalts are considered by many (see, for example, refs. 2 and 3) to represent sub-crustal material. Assuming this to be a valid hypothesis, the occurrence of similar nodules in this phonolite would be evidence that it too was generated at sub-crustal levels.

Other evidence that some phonolite may originate at great depths is less directly provided by recent investigations of strontium isotope ratios in carbonatites and other rocks from alkaline igneous complexes[8,9]. The results are shown to be consistent with at least a sub-sialic source, both for the carbonatites and for the associated, comagmatic, igneous rocks. Phonolitic activity is not infrequently associated with carbonatite centres, as in East Africa, where field associations at least suggest that it may well be genetically related to carbonatite (see ref. 10), and could therefore have been generated from a similar deep-seated source.

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