AN HYPOTHESIS ON THE ORIGIN OF ALKALINE ROCKS SUGGESTED BY THE TECTONIC SETTING OF THE MONTEREGIAN HILLS

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ABSTRACT

The emplacement of the Monteregian igneous rocks was controlled by tectonic features at least 1500 miles long and 600 million years old. Repeated episodes of alkaline igneous activity have occurred along this complex feature at intervals of roughly 200 million years. It is suggested that the persistence of alkaline activity is due to desilication of solid and liquid silicate masses by flux of an aqueous phase through them. Diffusional and flow processes in a continental crust above a rising convection current concentrate water in sufficient amounts to make desilication a significant process. Desilication by vapour flux avoids the thermal barriers encountered in other desilication hypotheses either by lowering the solidus temperature of the barrier, or by creating masses of solid alkaline rocks to serve as parents for later alkaline igneous rocks generated by partial melting. The process is self-stabilizing and tends to lead to extended periods of alkaline igneous activity. Within the mantle it leads to conversion of basaltic magmas into olivine nephelinites, the parent magma of mafic alkaline rocks suggested by experimental evidence; within the crust it offers a means by which nepheline syenites and related rocks can be generated by anatexis.

The Monteregian hills form a chain of alkaline igneous bodies roughly 120 miles long and 120 million years old. As pointed out by Kumarapeli & Saull (1966) and recently documented by Doig & Barton (1968), this group of alkaline intrusions is only a link in a much longer chain of alkaline igneous rocks of varying ages and styles. Figure 1 shows the St. Lawrence valley rift system according to Kumarapeli & Saull, together with the known occurrences of Phanerozoic alkaline igneous rocks in eastern Canada. With the possible exception of Aillik Bay, every occurrence lies within 50 miles of the rift system. A very considerable scatter in ages is evident, but a tendency to fall into three groups is apparent. The oldest, with radiometric ages ranging from 500-600 million years, years, includes the Lake Nipissing alkaline province, dikes southeast of Montreal, the Mutton Bay carbonatite, and the Aillik Bay lamprophyres. An intermediate group has ages ranging from 350-450 million years, including Brent, *the Bon Conseil mica pyroxenite*, Francon quarry carbonatite, and the Chatham and Rigaud stocks. The youngest occurrences give ages ranging from 120 to 200 million years, and include the Monteregian province, as well as numerous outlying occurrences ranging from James Bay to Newfoundland. There is sufficient scatter in the ages to suggest that alkaline igneous activity has been intermittently active along this system of normal faults for 600 million years.

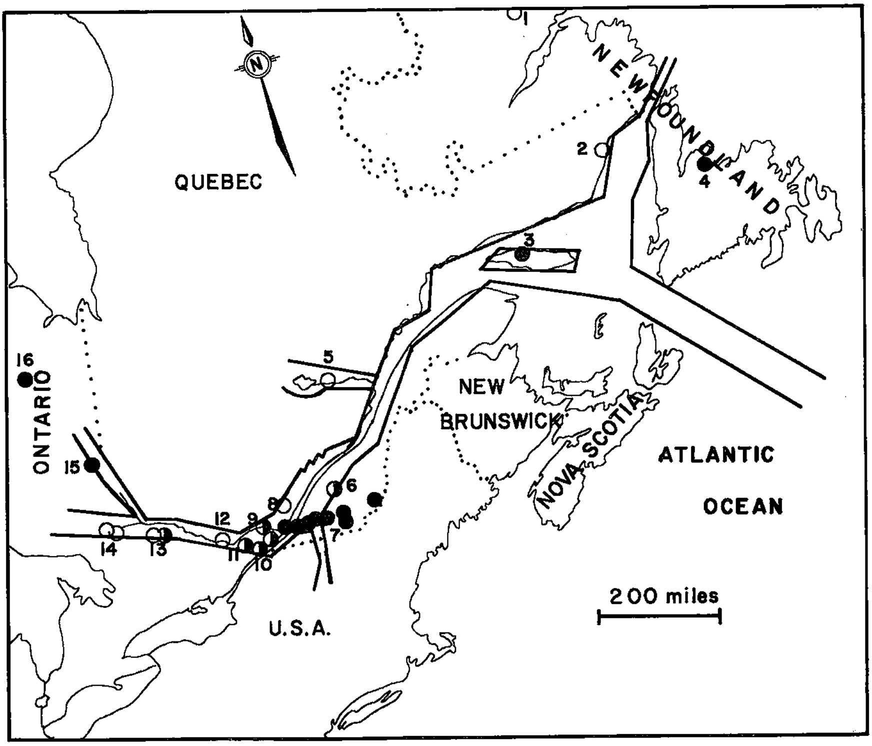

FIG. 1. Distribution of dated alkaline igneous rocks of Phanerozoic age in eastern Canada.

The boundaries of the St. Lawrence rift system are shown in heavy lines from Kumarapeli & Saull (1966).

1 — Aillik Bay lamprophyre swarm, 2 — Mutton Bay syenite and carbonatite, 3 — Anticosti Island lamprophyre, 4 — Notre Dame Bay lamprophyre swarm, 5 — Chicoutimi carbonatites, 6 — Bon Conseil mica pyroxenite, 7 — Monteregian Hills, 8 — Ste. Sophie dikes, 9 — Chatham-Grenville stock, 10 — Rigaud stock, 11 — Francon quarry carbonatite dike, 12 — Onslow syenite dike, 13 — Bren (alnöite 586 m.y., trachyte 345-420 m.y.), 14 — Manitou Island complex, 15 — Kirkland Lake kimberlite, 16 — Coral Rapids lamprophyres.

Data from Doig & Barton (1968), various age dating publications of the Geological Survey of Canada, and from M. Shafiqullah (personal communication). Filled circles show rocks with radiometric ages of 100-200 million years, half filled circles show ages of 350-450 million years, and open circles show ages of 500-600 million years.

The igneous activity along this rift system has been entirely of alkaline type, although there have been wide variations in the chemistry of the rocks emplaced. There appears to be an essential relation between this complex system of normal faults and persistent alkaline igneous activity. A similar relation seems to hold true for the African rift valleys, for the Gardar igneous province of Greenland, and for other continental alkaline igneous provinces associated with rift systems.

The composition of alkaline igneous rocks in these provinces appears to fall into two rather sharply defined groups. One is mafic to ultramafic, ranging from essexite to pyroxenite and peridotite. The other is salic, comprising syenite, nepheline syenite, phonolite and related rocks. Many occurrences of alkaline rocks are comprised entirely of one or the other of these groups. Where both groups are present in a single occurrence, relations between them are often such as to suggest two separate sources of magma, or even liquid immiscibility. Within the Monteregian province we might mention the sharp contrast between the two halves of Mont St. Hilaire, one ranging from essexite to pyroxenite, the other comprising feldspathoidal syenities (Pouliot 1969). Even more striking is the presence of ocelli of syenite within lamprophyric dikes with textures which suggest liquid immiscibility (Philpotts & Hodgson 1968). Few reliable data appear to exist on the proportions of the two groups occurring in various alkaline igneous provinces, but most general descriptions suggest that the volume of syenite, nepheline syenite and related rocks is comparable to, or excedes the volume of mafic alkaline rocks.

Yoder (1969) drawing on the results of many years of experimental work has shown that the composition and order of emplacement of many mafic alkaline rocks may be explained by fractional crystallization from a suitable parent magma (see also Schairer, Tilley & Brown 1968, Schairer & Yoder 1963). Two considerations militate against accepting fractional crystallization as the sole mechanism of generation of alkaline rocks : (1) the composition of the most plausible assumed parent (olivine nephelinite) appears from other work (*cf.* Runcorn 1967) to be an unlikely component of the upper mantle, and (2) such fractionation trends give rise to negligible amounts of nepheline syenite and related rocks, which are a major, or dominant component of many alkaline complexes.

The compositions of many nepheline syenites, and some ijolites on the other hand can be explained by supposing them to be the low melting fraction of an appropriate silica-undersaturated salic parent (Hamilton & MacKenzie 1965, Bailey & Schairer 1964). The problem with this explanation is the identification of an appropriate parent.

The origin of alkaline rocks thus appears to be strikingly similar to that of igneous rocks of non-alkaline origin. The mafic alkaline rocks are derived by partial melting of a mafic to ultramafic alkaline parent while the salic members are derived by partial melting of a salic alkaline parent. The origin of the parent remains problematic. As Daly and Shand (see Shand 1945) pointed out many years ago alkaline rocks can arise from sub-alkaline rocks by a process of desilication. To show the basis of this hypothesis, Table 1 compares the composition of an alkali olivine basalt with that of an olivine nephelinite, and a granodiorite with a nepheline syenite. By extracting roughly 10 percent SiO_2 and 3 percent Al_2O_3 from an alkali olivine basalt, the composition can be converted to that of an olivine nephelinite. A more drastic desilication of a normal granodiorite, produces a composition of a nepheline syenite. Such desilication cannot be produced by limestone syntexis (as proposed by Day and Shand) because the liquids would crystallize before they were able to cross the thermal barriers separating nepheline normative rocks from less alkaline varieties. It appears plausible however that efficient desilication might be accomplished by a flux of water through the magma, or through a solid prior to partial melting.

Table 2 lists the meagre experimental data available on the solubility of solid and liquid silicates in water. At pressures up to 10 kilobars, SiO_2 is extracted from the silicate phase, often in spectacular amounts. The only exception to this generalization is the work of Burnham (1967) with Cl^- containing solutions. However Burnham also found that the

TABLE 1. EFFECT OF DESILICATION ON ALKALI OLIVINE BASALT AND ON GRANODIORITE

	1	2	3	4	5	6	7	8
SiO_2	67.4	25	56.6	56.0	46.4	10	42.3	42.2
TiO_2	0.58		0.77	0.66	2.63		3.23	2.90
Al_2O_3	15.8		21.1	21.6	14.8	4	12.5	11.8
Fe_2O_3	4.28		5.71	4.62	12.5		14.4	11.8
MgO	1.57		2.09	0.77	9.52		10.9	13.2
CaO	3.46		4.51	2.10	10.7		12.5	13.0
Na_2O	3.84		5.13	8.84	2.63		3.06	3.16
K_2O	3.07		4.09	5.34	0.95		1.11	1.44

Column 1 — Average granodiorite (from Nockolds, *Bull. Geol. Soc. Amer.*, **65**, 1007) ; Column 2 — Composition of material assumed removed ; Column 3 — Composition of residuum after removal of column 2 ; Column 4 — Average nepheline syenite (Nockolds, *op. cit.*) ; Column 5 — Average alkali basalt (Nockolds, *op. cit.*), Column 6 — Composition of material presumed from column 5 ; Column 7 — Residuum after removal of column 6 ; Column 8 — Average olivine nephelinite (Nockolds, *op. cit.*).

All analyses recalculated to 100 per cent.

presence of CO_2 in the aqueous phase markedly depressed the content of alkalies relative to silica and alumina. Since CO_2 would appear to be much more abundant than Cl^- as a component of fluid phases in contact with alkaline rocks, the net result is probably an enhancement of desilication due to presence of components other than water in the fluid phase.

Table 2 shows the possibility of desilication of silicate rocks by flux of water through them. It does not suggest a mechanism by which this could be accomplished, or show whether such desilication could be a significant factor under plausible geological conditions. A possible geometry for a rift system is shown in Figure 2, (Freund 1966). If rifts develop over upwelling currents of material from the mantle, an upbulge in the isotherms will occur in the region of the rift. This rise in temperature may be barely perceptible at the surface due to the low thermal conductivity of the sedimentary filling of the rift, but it must be significant at depth. Now we assume the rising column of material to mark a site at which devolatilization of the mantle procedes. If the volatile content of the ascending material increases to the extent that a separate aqueous phase is formed, this phase will migrate upward into the bulge carrying with it the most soluble parts of the rising column of silicates.

Consider the crust surrounding the bulge in the isotherms, we assume an aqueous volatile phase to be present, either as an original feature, or due to dehydration of the ascending convection current. As this aqueous phase is heated it will dissolve its surroundings, and due to the temperature gradients, concentration gradients will exist in the fluid phase. These temperature gradients lead to migration of material away from the high

TABLE 2. SOLUBILITY OF SOME SILICATES IN AQUEOUS SOLUTION

Species	T	P	Solvent	SiO_2/rest (initial)	SiO_2/rest (solution)	Wt. % Solute
quartz	160–1130	1–10	H_2O	∞	∞	0.007–47
K-spar	740-935	2–6	H_2O	3 : 1	3.2 : 1–12.7 : 1	0.52 – 6.94
albite	350–650	1–4	H_2O	3 : 1	3.1 : 1– 8.9 : 1	0.19 – 1.21
anorthite	"	"	H_2O	1 : 1	1.5 : 1–16.9 : 1	0.11 – 0.67
pegmatite	500–700	2–9	H_2O	4.3 : 1	8.3 : 1– 7.7 : 1	1.31 – 8.98
leucite	740–935	3–7.5	H_2O	1 : 1	2 : 1– 1.2 : 1	1.28 –13.20
enstatite	600	1	H_2O	1 : 1	5.32 : 1	0.056
quartz + hematite	500	1	H_2O	1 : 1	296 : 1	0.30
forsterite	200–900	1–4	H_2O	1 : 2	very large	?

Ratio of SiO_2/rest quoted in mols, *e.g.* albite consists of one mol K_2O, one mole Al_2O_3 and 6 mols SiO_2, the ratio SiO_2/rest is therefore 6/2 or 3 : 1. Data are compiled from Handbook of Physical Constants (Revised Edition), *Geol. Soc. America, Mem.* **71**, Morey & Hesselgesser (1951), and Currie (1968, and unpublished).

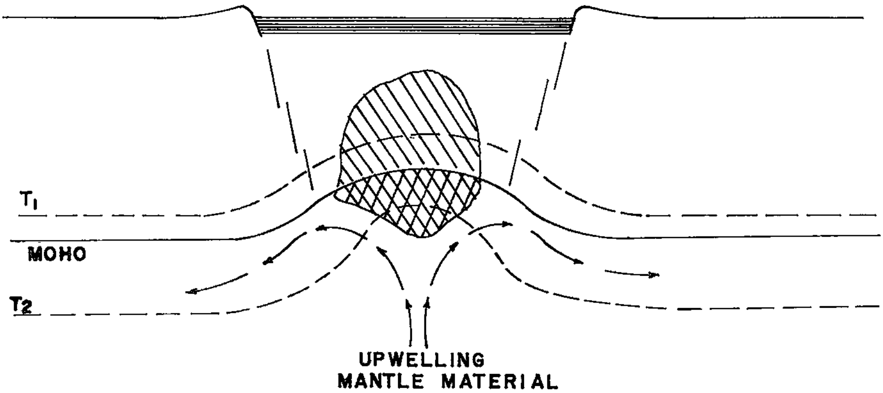

Fig. 2. A model of a rift beneath a continent (after R. Freund 1966). The dashed lines T_1 and T_2 show the assumed configuration of isotherms in the vicinity of the rift. The cross hatched region is at the stagnation point of the flow, and is trapped there. The hatched area above it is the favourable region for desilication in the crust.

temperature-high pressure regions, (since these are the regions in which solute concentrations are highest, compare Burnham (1967), Currie (1968)). The effectiveness of such transport can be estimated from the diffusion coefficient, which can be approximated knowing the temperature, the viscosity of the solute at the assumed P-T conditions, and the radius of the diffusing particle (Walton 1960). The radius of diffusing particles in supercritical solutions is poorly known, but any value between 1 and 10 angstroms gives diffusion coefficients for water of order 10^{-3} at 600°C and 2 kbars. For temperature gradients of 30° per kilometre this produces mean diffusional displacement of about 1 km/year. Now if the volume of the system is preserved, the solute can only migrate down the P-T gradient if the solvent migrates in the opposite direction. This phenomenon is precisely analogous to the well-known counter-gradient migration of 'holes' and ions observed in many solids, (Frenkel 1946). The net result of diffusion will thus be formation of desilicated volatile-rich material in the region of the upbulged isotherms.

The concentration of water in the region of the upbulged isotherms cannot continue indefinitely. It may be intercepted at an early stage by open fractures, but since the material is assumed to be plastic, or even liquid, this is not very likely. The rise in pressure must put a catastrophic end to the accumulation of volatiles. The explosive escape of volatiles will lead to a still further desilication of the non-volatile phase, since the non-equilibrium solubility of silica from silicate minerals is much higher than the equilibrium solubility (Currie 1968, Adams 1968). Since water is less dense than most other volatiles at the temperatures and pressures of interest, it will escape preferentially, leaving the residual fluids enriched in the denser gases, notably CO_2. The gradual build-up and escape of volatiles may provide a mechanism for periodic igneous activity. According to this argument, successive batches of magma should become progressively richer in CO_2.

Thus far we have made no estimation of the efficiency of the proposed desilication process, or its water requirements. In the present rudimentary state of the composition of aqueous phases in equilibrium with solid and liquid silicate mixtures, such estimates are extremely unreliable. A crude calculation can be made by supposing enstatite to be a major component in the parent material, and applying the data of Morey & Hesselgesser (1951) (see also Table 1). The mol ratio of SiO_2/MgO in the solution at 600°C and 1 kbar is 5.32 to 1. Taking the measured solubility of enstatite, and the equation

$$2\ MgSiO_3 - 0.2\ MgO - 1.1\ SiO_2 = 0.9\ Mg_2SiO_4$$

appropriate to the SiO_2/MgO ratio of the solution, it is found that 32.8 mols of water will convert 1 mol of enstatite to forsterite, with a decrease of silica content of 17 per cent. Other desilication reactions, for example albite nepheline seem to require about similar water volumes, which require that something like 1-2 mols of water pass through each cubic centimetre of rock during the desilication process. Supposing that the water content of the parent material was 2 per cent, (about 0.003 mols per cubic centimetre), this would require something like 350 cubic centimetres of rock to be dehydrated to develop each cubic centimetre of alkaline magma. We have already noted that water is concentrated from the surrounding crust into the developing alkaline rocks. Examination of Figure 2 suggests that the top part of the rising convection column may become mechanically trapped in the upbulged portion, and form a conduit through which the rising convection column is dehydrated. Such prisms of volatile rich material may be the cause of the anomalously low density and low seismic velocity prisms commonly found beneath rifts (Cook 1966). In any event the indicated efficiency (0.3 per cent) does not appear completely unrealistic, and is probably capable of accounting for the relatively small volumes of alkaline rocks observed.

The generation of alkaline rocks by this process must encounter the thermal barriers which have proved fatal to the limestone syntexis hypothesis of origin of alkaline magmas. There are significant differences in the manner in which these thermal barriers operate however. In the case of desilication by volatiles, the process of desilication tends to raise the volatile pressure in the magma, and hence to lower its melting point. This factor by itself may be sufficient to permit the melt to hurdle the thermal barrier. If it is not, and the melt crystallizes in the vicinity of the thermal barrier, the process of desilication continues in the solid, so long as the flux of aqueous solution is present. This process would leave substantial volumes of solidified alkaline rocks in the region of strong fluxes of volatiles. These rocks are a potential source of alkaline igneous rocks formed by partial melting. Such favourable source rocks may be a major factor in the persistent reappearance of alkaline igneous activity along the same structure.

A further cause of the persistence of igneous activity appears from examination of the model (Figure 2). Concentration of volatiles is a highly efficient method of transporting heat, and maintaining the upbulge of the isotherms. When such volatile-rich, desilicated material becomes dehydrated by eruption or explosion, its density will tend to rise above that of its surroundings and the residual material will sink, perpetuating the convective cycle. The cycle of convection-dehydration-desilication thus tends to be self perpetuating. This cycle needs a reasonably thick insulating blanket and a source of water over the convecting stream. From this consideration, it seems clear that persistent alkaline magmatic activity is much more probable on continents than in the oceans.

We may distinguish three possible courses of alkaline igneous activity resulting from this model of the crust and upper mantle (1) generation and intrusion of nepheline syenite complexes by anatexis of desilicated crustal material with little or no contribution of mantle material. Carbonate rich phases would be a late stage according to this model. No example of this type appears to occur within the Monteregian province, but the Mutton Bay syenite and carbonatite is a possible example from the St. Lawrence rift system. (2) volatile-rich alkaline basic rocks consisting essentially of upper mantle material. These will become increasingly poor in silica and rich in CO_2 as igneous activity progresses. Most of the Monteregian intrusions are probably of this type, and according to this scheme, the ages of the intrusions should decrease from east to west, with the Oka carbonatite forming the youngest mass (3) combined intrusions in which the basic alkaline magma has passed through, or generated, anatectic syenitic magma during ascent. Homogenization of such hybrids may be prevented by immiscibility (Philpotts & Hodgson 1968). A possible example in the Monteregian hills is Mont St. Hilaire.

In summary; (1) Flux of aqueous fluids through either solid or liquid masses of silicate rocks will desilicate them. (2) Diffusional and flow processes in a continental crust above a rising convection current concentrate water in sufficient amounts to make desilication a significant process. (3) Desilication by vapour flux avoids the thermal barriers encountered in other desilication hypotheses, either by lowering the solidus temperature of the barrier, or by creating masses of solid alkaline rocks to serve as parents for later alkaline igneous rocks generated by partial melting. (4) The process is self stabilizing, and tends to lead to repeated periods of alkaline igneous activity. (5) Within the mantle, the process offers a means by which presumed common rocks may be converted to the parents of alkaline mafic rocks suggested by experimental work. (6) Within the crust it offers a means by which nepheline syenite and related rocks may be generated by anatexis.

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