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PETROGENESIS OF BASALTS FROM THE ARCHEAN MATACHEWAN DIKE SWARM SUPERIOR PROVINCE OF CANADA

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ABSTRACT

The Matachewan Dike swarm of eastern Ontario comprises Archean age basalts that have been emplaced in the greenstone, granite-greenstone and metasedimentary terrains of the Superior Province of Canada. The basalts are Fe-rich tholeiites, characterized by the near ubiquitos presence of large, compositionally uniform, calcic plagioclase (AN 85±5). Major and trace element whole-rock compositions, along with microprobe analyses of constituent phases, from a group of dikes from the eastern portion of the province, were evaluated to constrain petrological processes that operated during the formation and evolution of the magmas. Three compositional groupings, have been identified within the dikes. One group has compositional characteristics similar to modern abyssal tholeiites, e.g. light-REE depleted, and is termed morb-type here. A second group, enriched in incompatible elements and light-REE enriched, $(La/Sm)_n > 1.80$, is referred to as the enriched group. The third more populated group has intermediate characteristics and is termed the main group. Owing to this latter group's larger and more coherent compositional variation, geochemical modeling was concentrated here. Although some dikes of the main group are relatively uniform, others display significant variation on the outcrop scale. Geochemical trends of the intradike suite are parallel to those of the interdike suite and are considered together. Major element mixing models suggest that the compositional variation of the main group can be accommodated by fractionation of assemblages consisting of variable proportions of olivine, clinopyroxene and plagioclase. Trace elements, however, cannot be accommodated at the same fractionation level as the major elements, indicating that processes more complex than simple crystal fractionation must have operated during main group evolution. The open-system process of periodic replenishment can explain both the uniform composition of the plagioclase megacrysts as well as the apparent decoupling of the major and trace element compositions. Combined replenishment-fractionation, however, cannot account for the compositional variations between the three groups of the dikes. The observation of both morb-type and enriched compositions within a single dike of the SEC strongly argues for the contemporaneous existence of magmas derived through different processes. Mixing calculations suggest that two possibilities exist. The least evolved basalts of the main group lie on a mixing line between the morb-type and enriched group, suggesting mixing of magmas derived from heterogeneous mantle. Alternatively, mixing of magmas derived from a depleted mantle with heterogeneous Archean crust can duplicate certain aspects of the Matachewan dike compositional array.

INTRODUCTION

Basaltic rocks constitute a significant portion of the volcanic rocks of the Archean crust. They occur as flow rocks within greenstone and greenstone-granite terrains, and are compositionally similar to temporally and spatially related mafic intrusions. In addition, basalts comprise large Archean dike swarms, the areal extent of which results in the dikes crossing litho-tectonic boundaries along which Archean blocks of markedly different character are juxtaposed. Interest in Archean basalts stems from the information they might provide relative to crustal genesis and plate tectonic processes in the early Precambrian.

This particular study concerns the Matachewan dike swarm (MS) of eastern Ontario. This swarm was emplaced over an area exceeding 250,000 km2 in a stable cratonic "granitic"-greenstone terrain of probable continental origin (1,2). The dikes are tholeiitic and cross lithologies varying from mafic to felsic volcanics, volcaniclastics and intermediate to silicic plutonic bodies (3,4). The majority of the MS dikes host megacrysts of plagioclase of uniform composition (AN 85±5), similar to constituent plagioclase in Archean anorthosites (2,5,6). As a result of this megacryst connection, a geochemical study of a portion of the MS dikes was undertaken to determine the magmatic processes involved in basalt production and evolution with the ultimate goal of constraining anorthosite genesis. In this paper, we report the results of geochemical modeling of the basalts and the resulting implications for their open-system evolution.

GEOLOGIC SETTING

The Matachewan dike swarm occurs within the Superior Province of eastern Ontario (fig. 1), crossing several subprovinces (7). These subprovinces are characterized as greenstone-tonalite ("granite"), paragneiss and batholithic terrains, differing in the proportions of different rock types, metamorphic grade and structural style (8). The subprovinces can be described (7, 9) as metavolcanic-rich belts (e.g. the Abitibi, Wawa and Wabigoon subprovinces) separated by intervening metasedimentary belts (e.g. the Quetico subprovince), although the boundaries between some belts are tectonic in nature (5). Plutonic rocks are as diverse as the volcanic (3, 7), although tonalite-granodiorite and monzonite-quartz monzonite appear to dominate (4). Plutons as evolved as granite, as well as syenites, are found (7). Layered mafic intrusions, often with associated anorthosites, also occur within the Superior Province (10, 11).

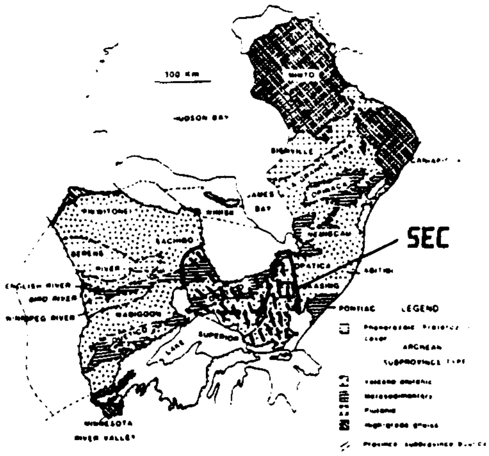

Figure 1. Generalized geologic map of the Superior Province (from Card(7)). Trend and distribution of the Matachewan dike swarm is outlined and the southeast cluster (SEC), emphasized in this study, is indicated.

The ages of magmatic, metamorphic and tectonic events were broadly synchronous in the Superior Province but initiated somewhat earlier in the northern subprovinces (7). Within the Wabigoon, Wawa and Abitibi belts (Fig. 1), U-Pb zircon dates indicate that activity occurred over the period of 2790-2660 Ma (7, 9, 10), and can often discern an early volcanic-plutonic event, a middle tectonic-metamorphic event and a late plutonic event (7, 9). The Matachewan dikes were emplaced after the major periods of magmato-tectonic activity (12) in the approximate time frame of 2.5 to 2.6 Ga (13). The subparallel trend of these dikes suggests emplacement during extensional tectonics.

SAMPLE DISTRIBUTION AND CHARACTER

Geochemical modeling was concentrated on samples from a portion of the MS, the southeast cluster (SEC) of figure 1, because of higher sample density and greater compositional variability. Most of the SEC dikes contain large (up to 20 cm) plagioclase phenocrysts (2). These phenocrysts are often irregularly distributed (1) and flow differentiation processes are evident in outcrop. Recognizing non-liquid compositions, produced by cumulate processes, on geochemical variation diagrams is often difficult. Frequently, more than one subparallel liquid descent line is present producing an apparent scatter. Europium anomalies (Eu/Eu*), which monitor the participation of feldspar in magmatic evolution, are unequivocal as an indication of plagioclase accumulation in basalts only when Eu/Eu* > 1.0. If the basalts have evolved a negative Eu anomaly (i.e. Eu/Eu* < 1.0), subsequent plagioclase accumulation may occur without a resulting positive Eu anomaly, while producing a trend similar to crystal fractionation. Major elements, however, are controlled by phase equilibria. Significant departures from evolution lines may therefore indicate compositions that were never liquids. On a CaO-MgO diagram, the bulk of the MS dikes define a single linear array. Several, however, plot off this trend, often along a line towards either olivine or plagioclase. Because it is suspected that these samples reflect the presence of cumulus minerals, these have not been considered in the modeling procedures below.

Modification of original magmatic concentrations through metamorphism, of concern here for the MS dikes, has been addressed by Pearce and Cann (14) and many others. In the SEC data, strong correlations exist between the immobile elements (e.g. Ti, Zr and Y) and most other elements. Exceptions are Rb, K, Ba and Sr, which, although showing considerable internal consistency, are scattered when plotted against Zr. These four elements are regarded to have been mobile during metamorphism and are not used in modeling, although it is suspected that the ratios of these components reflect magmatic values.

GEOCHEMISTRY

The MS basalts vary from olivine- to quartz-normative tholeiites. When plotted on the tectono-magmatic diagrams of Pearce and Cann (14), the MS rocks fall in the field of ocean-floor basalts, a characteristic of many basalts of greenstone belts (15). For the MS dikes, ratios K/Rb, K/Ba and Sr/Rb are more comparable to Type II than Type I basalts. In terms of the rare earth elements (REEs), the MS dikes vary from light-REE depleted to light-REE enriched (Fig. 2). In the latter case, the MS dikes are more similar to continental flood basalts (16) or oceanic island tholeiites and alkali basalts (16, 17) than abyssal tholeiites. The MS compositions reflect an Fe-enrichment trend (2); The MgO content of the least evolved SEC compositions is near the density minimum for tholeiitic magmas (18, 19).

The MS data define linear arrays in compositional space (e.g. Fig. 3) indicating that the magma(s) evolved through similar processes. Examination of figures 2 and 3 allow the delineation of three compositional groups within the SEC. The first, the morb-type, has low incompatible element concentrations (Fig. 3) and is light-REE depleted (Fig. 2), similar to abyssal tholeiites. A second, or enriched

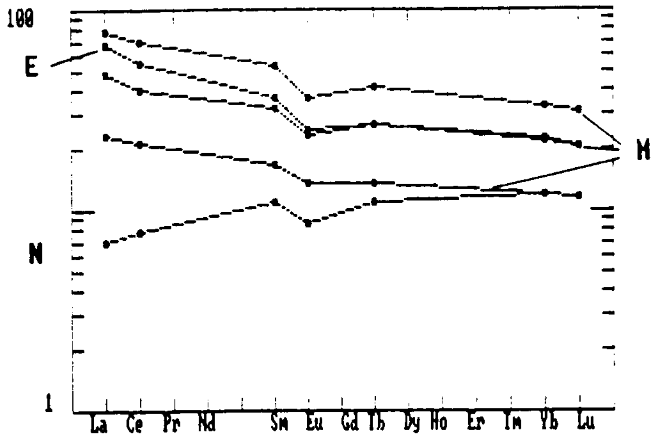

Figure 2. Rare earth element diagram for selected rocks of the SEC group. The symbol N denotes Morb-type; E the enriched group; M the main group.

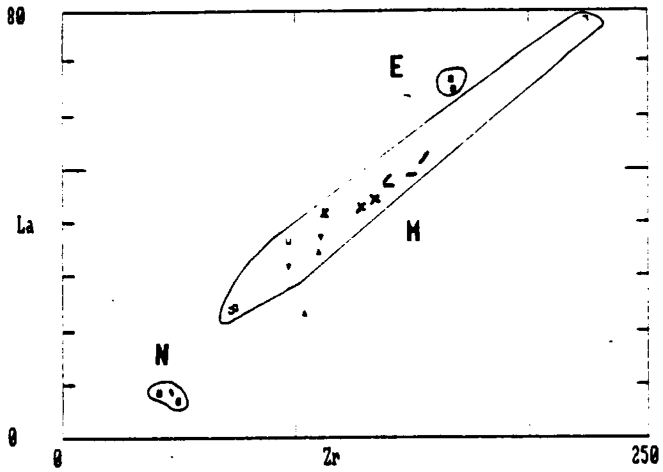

Figure 3. Zr versus La for the SEC rocks. Group designations as in figure 2. Common data symbols on the graph represent samples from the same dike.

group, is light-REE enriched (Fig. 2) and has high incompatible element concentrations (Fig. 3). The third, or main group, comprising the bulk of the SEC, has intermediate compositional characteristics.

Within the SEC, both intra- and interdike variations are found (Fig. 3). Intradike suites, collected at the same outcrop for a given dike, range from uniform to rather varied. The trajectories of the intradike variations are, however, subparallel to those of the interdike array, and are considered to have evolved through similar processes.

Two samples in figure 3 (+ symbols) are not dikes, rather they are older basaltic flow rocks. These flows are very similar to the morb-type dikes with the exception that the flows are less evolved (e.g. higher Mg numbers, Cr and Ni contents). It is suspected that magmas similar to the flow rocks were produced during Matachewan time. Accordingly, flow rock compositions have been used as parental liquids in some of the models below.

DISCUSSION

Linear compositional trends may result from variations imposed by the source, by the melting event, by chamber processes, by mixing, through crustal interaction and as a result of post-emplacement processes, acting independently or together. It is the purpose of the modeling here to determine: 1) what processes operated, 2) their relative contributions to the observed variations, and 3) when in evolution scheme the individual processes acted.

RESIDENCE CONTAMINATION

"Residence contamination" is the post-consolidation exchange of components between the wall-rock and the dike (20). Sample density in the present study is not sufficient to detect the compositional gradients in the dikes, nor is wall-rock data available in all cases. As a result, the role of residence contamination in the SEC could be quantitatively evaluated on only a few dikes. The compositions of the interiors and margins of relatively uniform dikes emplaced in different terrains were examined for compositional shifts that could be attributed to wall-rock exchange. No such shifts were observed. For example, dikes intrusive into "granitic" material were not enriched at the margins in elements such as Zr, La, Th and Y. Dikes intrusive into mafic terrains do not reflect enrichments of Ni, Sc, Co and Cr. One dike, emplaced along a granite-amphibolite contact was particularly useful. No compositional difference was detected between the interior and either margin (Fig. 4). On a regional scale, with the exception that the morb-type dikes appear to occur only in greenstone belts, no significant differences are apparent between those dikes emplaced in the greenstone versus "granitic" terrains (Fig. 5). Although this does not preclude residence contamination, it clearly limits its role to a minor one in the evolution of the main SEC group.

FRACTIONAL CRYSTALLIZATION

Fractional crystallization (FC) has undoubtedly operated

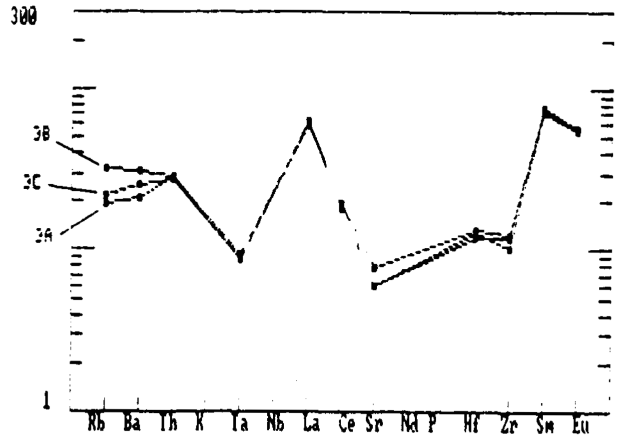

Figure 4. Spider diagram for a single intradike suite. Sample 3B is from the dike interior, 3A and 3C are adjacent to granite and amphibolite, respectively.

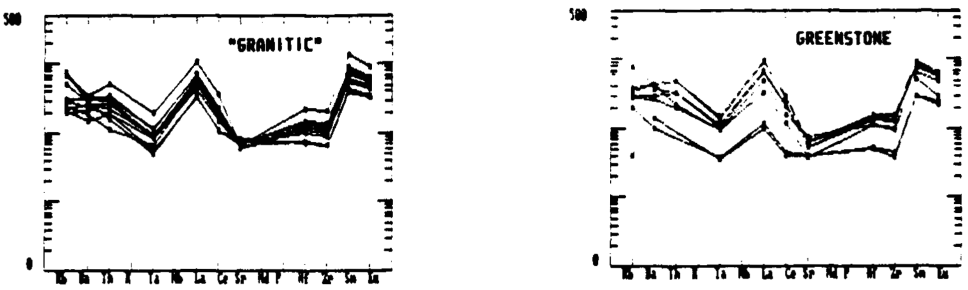

Figure 5. Spider diagram comparing compositions of SEC dikes emplaced in granitic and greenstone terrains.

at some level to produce the evolved SEC compositions. This is indicated by low Mg numbers (40.7-57.1), Cr (42-101) and Ni (40-80) contents and the Fe-enrichment trend. Additionally, the MS dikes plot along the 3-5 Kb plagioclase-olivine-clinopyroxene cotectic (21) as well as defining an array in Al2O3-CaO space along a plagioclase-clinopyroxene control line. It is important to note, however that the large variation in (La/Sm)n between the morb-type (0.62-0.74), the main- (1.39-1.58) and the enriched- (1.81-2.41) groups preclude FC from being the control of the intergroup compositional differences of the SEC. Simple FC cannot produce significant changes in this ratio. Covariations between Zr and Y, P, and La, and between La and Yb limit the roles of phases that can fractionate La and Sm, e.g. garnet, apatite, zircon and monazite.

To evaluate FC in the SEC main group, major element mixing models were performed using phenocryst and whole rock data of supposed evolved and parental compositions. In general, the lowest residuals were achieved for assemblages of olivine, clinopyroxene and plagioclase. Magnetite was not considered because it is not a phenocryst phase, because Ti is incompatible and because of the marked Fe-enrichment and lack of SiO_2 enrichment in the series (22). Successful models were achieved in some, but not all, members of both the intra- and interdike suites. In most dikes, the marginal samples were less evolved than those of the interior. In some dikes, however, the reverse is true.

The calculated assemblages are capable of producing the trace element variations observed, but at markedly different F values than that required by the major elements. In particular, the incompatible elements require that the F value be smaller, e.g. the fractionation greater, than that predicted by the mixing models. This problem cannot be overcome by assuming different partition coefficients (Kd). Calculated bulk Kds in the assemblages are already low (e.g. $< 0.05-0.15$) for these elements. To produce the observed variation within the restrictions of F required by the mixing models, the Kd values must be negative, varying for example, from -0.32 for Zr to -0.67 for La, an impossible situation. The decoupling of the major and trace elements indicates that simple FC is not capable of accounting for the compositional variability of the main SEC group.

The failure of the FC model suggests that the compositional variation observed within single dikes was not the result of insitu processes. This suggests that the composition of the magma emplaced in the dike changed with time. The dikes should not, therefore, be viewed as the result of "instantaneous" emplacement of a homogeneous magma. Rather, they record a history of evolution that occurred prior to dike formation.

IMPLICATIONS OF THE PLAGIOCLASE MEGACRYSTS

Constraints to petrogenetic models for the SEC main group are provided by the plagioclase megacrysts. A compositional variation of less than three AN units within a single cryst requires growth in an essentially isothermal, compositionally uniform environment (2, 23). This compositional uniformity extends to all megacrysts within the MS dikes, where AN contents are 85±5 regardless of the dike's geologic setting and trace element concentration levels (2). Further, the observed partitioning of REE between plagioclase megacrysts and matrix indicates equilibrium between megacryst and host dike (2, 23).

These observations indicate that the megacrysts grew in equilibrium in an environment characterized by uniform major element, but varying trace element composition. This is not the environment expected in a chamber undergoing simple FC. It is, however, expected in a chamber undergoing continuous fractionation with periodic magma replenishment (24-27). Replenishment supplies the required thermal input; Major elements become "perched" (28) while incompatible trace elements continue to evolve.

PERIODIC REPLENISHMENT MODEL

Detailed microprobe traverses across single plagioclase megacrysts reveal subtle but significant compositional variations, manifest as smooth oscillations of 1-2 AN units about a mean value (29). This suggests periodic rather than continuous replenishment. We have developed a geochemical model of periodic replenishment from the physical model presented below.

Figure 6 represents the physical model of replenishment used in this study. Activity begins with the emplacement of magma of composition Co in a shallow crustal chamber (Fig. 6a). The density of Co is greater than the country rocks and as the magma was emplaced during extensional tectonism, it could not have risen as an independent blob. Rather, it must be supported by a magma column plumbed into a deeper chamber (?) fed from upwelling melting mantle. Although perhaps occurring continuously, we consider the following processes to proceed as steps. Fractional crystallization proceeds in the floor, sidewall and roof region (Fig. 6b). We assume that during this crystallization interval, no leakage occurs (27, 30). We further assume that mixing within the chamber proceeds so as to produce uniform derivative melt (Cl) after (1-F) of crystallization. After this period of crystallization, a replenishing event occurs in which a mass (Mr) of replenishing magma of composition Co enters the chamber (Mr may be >, = or < 1-F) and that Co and Cl mix uniformly (31) to produce Cl' (Fig 6c). During the next cycle, Co mixes with Cl' to produce Cl'', etc. Marginal crystallization reduces chamber volume. Therefore, the replenishment event will result in chamber growth, dike emplacement or eruption to the surface (Fig. 6d). For simplicity we assume that the magma thus emplaced will have the composition Cl'. In

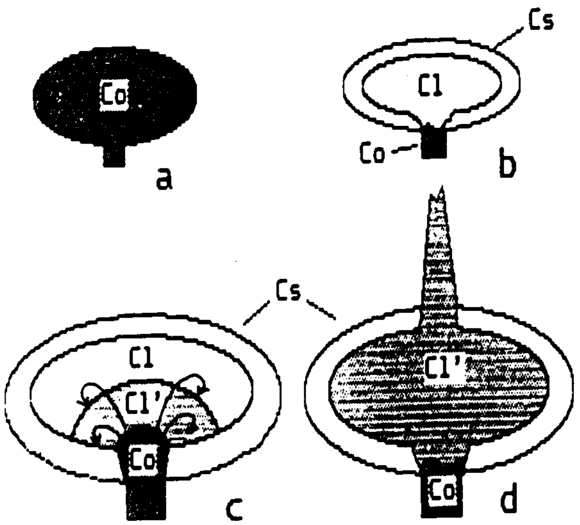

Figure 6. Diagram of replenishment process. Initial magma (Co) is emplaced (a) followed by marginal crystallization (Cs) yielding composition Cl (b). Replenishment by Co with subsequent mixing with Cl yields Cl' (c) which is emplaced as a dike (d). See text.

practice, dike emplacement may occur simultaneously with replenishment, and after various stages of mixing. If mixing is incomplete, either during the fractionation interval, perhaps leading to a stratified magma chamber, or during the replenishment event, compositional endmembers (Co, Cl and Cl') may be forced into the dike conduit at different times (32), perhaps producing the intradike compositional variation observed.

Field evidence supporting multiple injection of magma into the dikes is provided by the non-uniform distribution of megacrysts in the dikes. The megacrysts are often segregated into planar zones subparallel to dike walls. In simplest form, there is only a single planar zone, near the dike center, probably the result of flow differentiation during a single emplacement event. In more complex occurrences, several zones occur at various locations within the dike, and are best explained by periodic pulses of magma entering the dike. As there are no chill zones evident in the complex dikes, the periodicity of emplacement must have been rather frequent. Hunter and Sparks (22) report that zonation in the Hekla (Iceland) system re-established itself in periods of tens to hundreds of years. Although influenced by dike wallrock temperature, if such timing occurred in the MS system, chill zones may not be expected.

Trajectories of periodic replenishment pass through the SEC main group (Figs. 7a,b), consistent with these rocks being derived through this process. Scatter is greater in

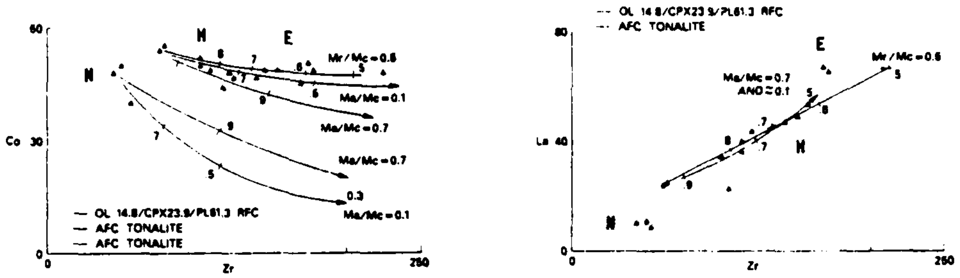

Figure 7. Variation diagrams for the SEC with morb-type, main- and enriched-groups indicated. Modeled are combined replenishment-fractional crystallization (Mr/Mc indicated) and combined assimilation-fractional crystallization (Ma/Mc indicated) using a tonalitic assimilant. Tick marks represent Mm/Mmo values. Fractionating assemblage in the models as indicated.

the Zr-Co plot than in the Zr-La diagram because of the large difference in bulk Kd values for the incompatible-compatible element set. The most compelling geochemical argument for replenishment is the restored agreement between major and trace element models. Above, the decoupling of major and trace elements was discussed in terms of the simple FC model. In particular, F values required by the different data sets did not agree. For the combined replenishment-fractional crystallization model (RFC), however, the F value required by the major elements is within the range of F (actually Mm/Mmo (33)) permitted by the trace elements. These observations, coupled with the requirements of the megacrysts, argue for the RFC model as the controlling process of the SEC main group. The process of periodic replenishment has been recognized in a number of layered mafic intrusions (e.g. 11, 34, 35), primarily as chemical reversals in cumulate sequences (36).

Several studies (e.g. 36, 37) have demonstrated that variations in the parameters of open-system evolution can significantly affect liquid compositions. Modeling during this project concentrated on the impact that varying the mass ratio of replenishing magma to cumulus phases (Mr/Mc) has on concentrations of elements of variable Kds. Modeling indicates that incompatible element ratios are preserved during replenishment. Further, compatible elements reach steady state concentrations for all mass ratios tested (Mr/Mc = 0.25 - 2.0), although for a given Mr/Mc, more cycles (i.e. a FC interval followed by replenishment) are required to reach steady-state. For a given Mr/Mc, it is the total amount crystallized that is important rather than the number of cycles. In other words, a given mass must be crystallized to reach steady state. If the fractionation interval is 10 percent, it will take twice as many cycles than if the interval is 20 percent. For Mr/Mc > 1.0, even incompatible elements reach steady state although a significantly greater amount of crystallization must occur. The modeling indicates that if one examines variation diagrams where a compatible element (Kd = 3.0) and a moderately incompatible element (Kd = 0.7) are plotted against an incompatible element (Kd = 0.1) the rate of replenishment might be evaluated. Figure 8 compares the predictions of the general model with the actual distribution of Ni (Kd = 2.57), Zn (Kd = 0.5) and Zr (Kd = 0.03) data for the MS dikes. Examination of the model and the

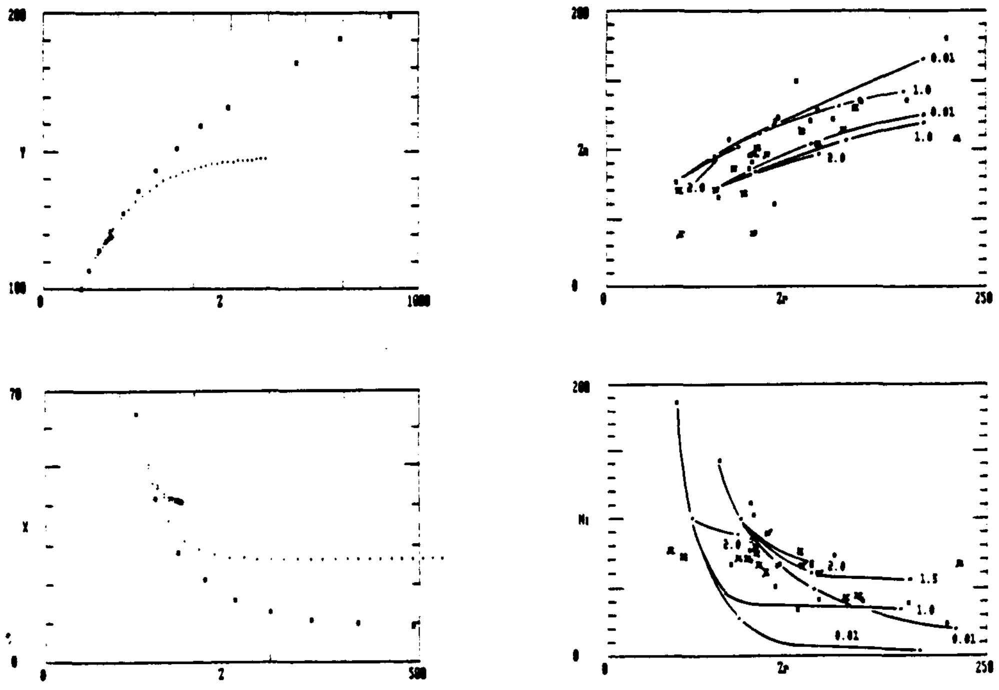

Figure 8. Trajectories of evolution during RFC at Mr/Mc of 0.25 (■), 1.0 (+) and 2.0 (○). Depicted is a compatible element X (Kd = 3.0) and slightly incompatible element Y (Kd = 0.7) plotted against an incompatible element Z (Kd = 0.1). For comparison, Ni (Kd = 2.57) and Zn (Kd = 0.5) against Zr (Kd = 0.03) is shown. See text for further discussion.

data indicate that the dikes may have evolved under variable replenishment rates, although the bulk of the compositions are most consistent with a value of Mr/Mc of less than one.

IMPLICATIONS FOR MULTIPLE PARENT LIQUIDS

The (La/Sm)n versus Zr variation (Fig. 9) reinforces the conclusion that the main group evolved through RFC processes, but clearly indicates that RFC cannot account for compositional differences between the morb-, main- and evolved groups. These intergroup variations may result from source effects, reflecting the trace element characteristics of differing mantle sources tapped during the melting. Alternatively, the compositional differences may reflect crustal interaction between the basalt magma and various crustal components. The possibility that both processes operated is not precluded.

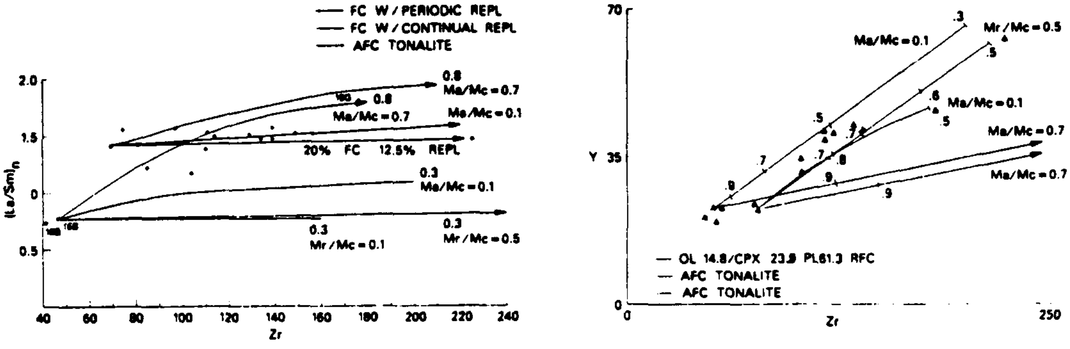

Figure 9. (La/Sm)n against Zr (a) and Y against Zr (b) for the SEC. Also shown are trajectories of various RFC and AFC models (see Fig. 7 and text).

Examination of figures 7 and 9 indicate that only low rates of assimilation (Ma/Mc = 0.1) during combined assimilation-fractional crystallization (AFC) of a tonalitic composition can be accommodated by the main group of the SEC. Higher rates produce unacceptable increases in (La/Sm)n and decreases in Co and Y. This is consistent with the implications of the major element compositions indicative of crystallization in the 3-5 Kb range (see above), where country rock temperatures were probably low. High rates of assimilation (Ma/Mc = 0.7) are capable of relating the morb-type compositions to the main group in terms of (La/Sm)n and Y, but not for La and Co. High rates of assimilation may be more consistent with emplacement at greater depths (i.e. the crust - mantle boundary) where country rock temperatures are significantly higher. Note that the main group does not lie along the morb trajectories in figure 9, but rather crosses them. This suggests that although the least evolved of the main group may be related to the morb-type compositions through AFC, the remainder of the series is not. The RFC model, with the least evolved of the main group representing Co, remains the most satisfactory model for the SEC main group.

It is apparent from the discussion above, that there is evidence for the existence of more than one "parental" liquid in the SEC, and that these liquids evolved more or less independently. Pertinent to this argument is the observation of the intimate coexistence of both morb-type and the enriched compositions. The REE data for these two groups, shown in figure 2, are from the same dike. No chill zone separates them, and other samples from the same dike have intermediate values. The implication is that the two limiting compositions were contemporaneous and were produced and/or evolved independently. Intermediate compositional groups (the main SEC group and other Ms dikes) might therefore represent variable mixing of the two endmembers. In figure 10, two possible mixing scenarios are displayed. In figure 10a, it is seen that a mixing line between morb-type and enriched compositions define the low-Zr boundary of the SEC data, suggesting that the least evolved, for a given range of Ti/Zr, SEC compositions lie along the mixing line. Also shown is a single FC-controlled trajectory; RFC produces a similar trend. This suggests that the least evolved compositions of the SEC were produced by variable mixing of magmas derived by melts from different sources, one depleted and one enriched. Compositions to the right of the mixing line may have evolved to their respective positions by RFC, related to a specific (?) Co on the mixing line.

As an alternative, figure 10b portrays the mixing of a morb-type melt with a "granitic" crustal component, which could either be a whole rock of this composition, or a crustal melt produced during the underplating of the crust by the basaltic magma. Clearly, the SEC data suggest the potential of crustal input (see also figure 9 and discussion above). FC/RFC trajectories are not shown because these processes have minimal effect on incompatible element ratios. Given the varied character of the Archean crust (e.g. 1, 2 and 7), it might be anticipated that a number of potential mixing lines could be drawn in figure 10b. In this regard, preliminary modeling suggests that mixing of morb-type magmas with amphibolite (Fig. 10b) may

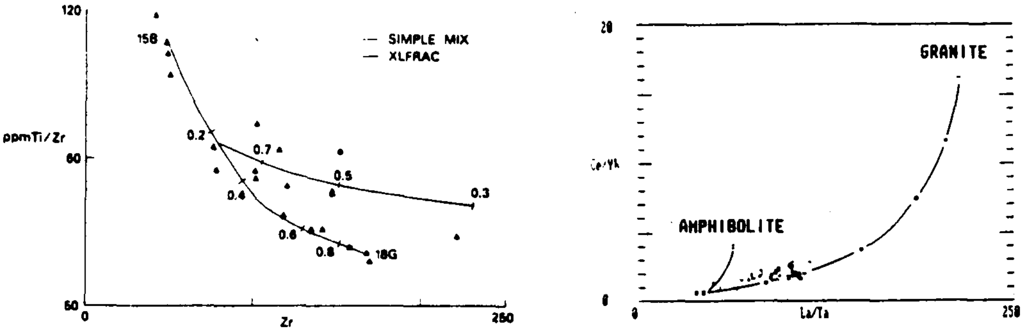

Figure 10. Variation diagrams plotting (Ti/Zr) against Zr, and (Ce/Yb) against (La/Ta) for the SEC. Mixing lines between morb-type (15B) and enriched (18G) compositions (a) and "granite" (b) are shown. Also shown in (a) is the predicted trend of FC (= RFC).

have operated to produce some of the SEC dike compositions.

Distinguishing between the two models portrayed in figures 10a and 10b will probably require isotopic studies. As indicated above, the two models are certainly not mutually exclusive. The compositions of the MS dikes may reflect mixing of multiple endmembers, e.g. depleted mantle, enriched mantle, granitic crust, amphibolitic crust, metasedimentary crust, etc.

CONCLUSIONS

1. The southeast cluster (SEC) of the Matachewan dike swarm can be divided into three compositional groups, based primarily on REE patterns. These groups comprise a morb-type (e.g. light-REE depleted), an enriched group having $(La/Sm)_n > 1.80$, and a main group with intermediate REE patterns.
2. The main SEC group can best be explained by combined replenishment-fractional crystallization (RFC) with variable ratios of replenishment to crystallization; Values were generally less than one. Low assimilation rates are permissible.
3. RFC cannot explain compositional variations between groups of the SEC. Mixing models indicate that mixing of mantle sources and/or interaction of mantle-derived magmas with heterogeneous crustal components may be responsible for intergroup variations.
4. The SEC field and geochemical data suggest a three-

tiered evolution model. The SEC intergroup variation resulted from either magmas being derived from heterogeneous mantle, with at least one component being depleted, or through the interaction of magmas, derived from depleted mantle, with heterogeneous Archean crust. In either of these cases, magma is envisioned to have pooled at the base of the crust. In the former case, the mantle-crust density boundary would trap the various mantle-derived liquids, allowing them to mix in variable proportions, producing the mixing line of figure 10a. In the latter case, the depleted melt would pool and assimilate crustal components, possibly reflected in figure 10b. A combination of both processes is quite possible. Magmas evolve at the base of the crust towards the density minimum. These low-density magmas would accumulate in the upper portions of these subcrustal magma chambers. Additions of new melt from below force these magmas into shallow crustal chambers. Through this re-occurring mechanism, the low-density basalt magmas become the replenishing magmas of the shallow RFC scheme (Fig. 6). Plagioclase megacrysts grow in this "uniform" environment. Dike emplacement, forming the Matachewan swarm, occurs from these shallow chambers. Emplacement occurs as pulses, possibly driven by periodic inputs to the shallow chambers. As a result of evolution and variable mixing within these chambers, successive pulses may differ in composition, leading to intradike variations. Flow differentiation during the periodic pulses of magma emplaced into the dikes produces irregular distribution of phenocryst phases, contributing to the intradike variation.

REFERENCES

1. Ernst, R.E.: Structural and Chemical Studies of Mafic Dike Swarms in Northern Ontario. Ont. Geol. Survey Misc. Pap., No. 106, 1982, pp. 53-56.
2. Phinney, W.C.; Morrison, D.A.; and Maczuga, D.E.: Anorthosites: an Analogue Study. Lun. Sci. Conf. XVIII, 1987, pp. 774-776.
3. Ontario Geological Map - East Central Sheet. Ont. Geol. Surv., Map 2393, 1977.
4. Berger, B.R.: Geology of the Hearst-Kapuskasing Area. Ont. Geol. Surv. Open File Rept., No. 5599, 1986, 88p.
5. Ashwal, L.D.; Morrison, D.A.; Phinney, W.C.; and Wood, J.: Origin of Archean Anorthosites: Evidence from the Bad Vermilion Lake Anorthosite Complex, Ontario. Contrib. Mineral. Petrol., v. 82, 1983, pp. 259-273.
6. Morrison, D.A.; Phinney, W.C.; and Maczuga, D.E.: Archean Anorthosites: Constraints on the Accumulation Process. Lun. Sci. Conf. XVIII, 1987, pp. 670-671.
7. Card, K.D.: Geology and Tectonics of the Archean Superior Province, Canadian Shield. LPI Tech. Rept., No. 86-04, 1986, pp. 27-29.
8. Beakhouse, G.P.; and McNutt, R.H.: Geochemistry of Granitoid Rocks from the Western Superior Province-Evidence for 2- and 3-Stage Crustal Evolution Models. LPI Tech Rept., No. 86-04, 1986, pp. 23-26.
9. Percival, J.A.: Metamorphism and Plutonism in the Quetico Belt, Superior Province, N.W. Ontario. LPI Tech Rept. No. 86-04, 1986, pp. 84-85.
10. Morrison, D.A.; Davis, D.W.; Wooden, J.L.; Bogard, D.D.; Maczuga, D.E.; Phinney, W.C.; and Ashwal, L.D.; Age of the Mulcahy Lake Intrusion, Northwest Ontario, and Implications for the Evolution of Greenstone-Granite Terrains. Earth Planet. Sci. Lett., v. 73, 1985, pp. 306-316
11. Morrison, D.A.; Maczuga, D.E.; Phinney, W.C.; and Ashwal, L.D.: Stratigraphy and Petrology of the Mulcahy Lake Layered Gabbro: An Archean Intrusion in the Wabigoon Subprovince, Ontario. J. Petrol., v. 27, 1986, pp. 303-341.
12. Hodgson, C.J.: The Structure and Geological Development of the Porcupine Camp-A Re-Evaluation. Ont. Geol. Surv. Misc. Pap., No. 110, 1983, pp. 211-225.
13. D.A. Morrison: Personal Communication, 1987.
14. Pearce, J.A.; and Cann, J.R.: Tectonic Setting of Basic Volcanic Rocks Determined Using Trace Element Analyses. Earth Planet. Sci. Lett., v. 19, 1973, pp. 290-300.
15. Grachev, A.F.; and Fedorovsky, V.S.: On the Nature of Greenstone Belts in the Precambrian. Tectonophysics, v. 73, 1981, pp. 195-212.

16. Basaltic Volcanism on the Terrestrial Planets. Pergammon Press, Inc., 1981, 1286 pp.
17. Nelson, D.O.; and Nelson, K.L.: Geochemical Comparison of Alkaline Volcanism in Oceanic and Continental Settings: Clarion Island versus the Eastern Trans-Pecos Magmatic Province. Mantle Metasomatism and Alkaline Magmatism, E.M. Morris and J.D. Pasteris, eds., Geol. Soc. America Spec. Paper 215, in press.
18. Huppert, H.E.; and Sparks, R.S.J.: Restrictions on the Compositions of Mid-Ocean Ridge Basalts: A Fluid Dynamical Investigation. Nature, v. 286, 1980, pp. 46-48,
19. Sparks, R.S.J.; Meyer, P.; and Sigurdsson, H.: Density Variation Amongst Mid-Ocean Ridge Basalts: Implications for Magma Mixing and the Scarcity of Primitive Lavas. Earth Planet. Sci. Lett., v. 46, 1980, pp. 419-430.
20. Fratta, M.; and Shaw, D.M.: 'Residence' Contamination of K, Rb, Li, and Tl in Diabase Dikes. Can. J. Earth Sci., v. 11, 1974, pp. 422-429.
21. Grove, T.L.; and Baker, M.B.: Phase Equilibrium Controls on the Tholeiitic Versus Calc-Alkaline Differentiation Trends. J. Geophys. Res., v. 89, 1984, pp. 3253-3274.
22. Hunter, R.H.; and Sparks, R.S.J.; The Differentiation of the Skaergaard Intrusion. Contrib. Mineral. Petrol., v. 95, 1987, pp. 451-461.
23. Maczuga, D.E.; Morrison, D.A.; and Phinney, W.C.: Rare Earth Elements in Plagioclase Megacrysts and Their Implications for Archean Anorthosite Genesis. Unpub. Ms.
24. Rhodes, J.M.; Dungan, M.A.; Blanchard, D.P.; and Long, P.E.: Magma Mixing at Mid-Ocean Ridges: Evidence from Basalts Drilled near 22 N on the Mid-Atlantic Ridge. Tecto-nophysics, v. 55, 1979, pp. 35-61.
25. Walker, D.; Shibata, T.; DeLong, S.E.: Abyssal Tholeiites from the Oceanographer Fracture Zone. Contrib. Mineral. Petrol., v. 70, 1979, pp. 111-125.
26. O'Hara, M.J.; and Matthews, R.E.: Geochemical Evolution in an Advancing, Periodically Replenished, Periodically Tapped, Continuously Fractionated Magma Chamber. J. Geol. Soc. London, v. 138, 1981, pp. 237-278.
27. Robson, D.; and Cann, J.R.: A Geochemical Model of Mid-Ocean Ridge Magma Chambers. Earth Planet. Sci. Lett., v. 60, 1982, pp.93-104.
28. O'Hara, M.J.: Geochemical Evolution During Fractional Crystallization of a Periodically Refilled Magma Chamber. Nature, v. 266, 1977, pp. 503-507.
29. Maczuga, D.E.; and Morrison, D.A.: Unpublished Data
30. Cann, J.R.: Rayleigh Fractionation with Continuous Removal of Liquid. Earth Planet. Sci. Lett., v. 60, 1982, pp. 114-116.

31. Campbell, I.H.; and Turner, J.S.: Turbulent Mixing Between Fluids with Different Viscosities. Nature, v. 313, 1985, pp. 39-42.
32. Blake, S.; and Campbell, I.H.: The Dynamics of Magma-Mixing During Flow in Volcanic Conduits. Contrib. Mineral. Petrol., v. 94, 1986, pp. 72-81.
33. DePaolo, D.J.: Trace Element and Isotopic Effects of Combined Wallrock Assimilation and Fractional Crystallization. Earth Planet. Sci. Lett., v. 53, 1981, pp. 189-202.
34. Pallister, J.S.; and Hopson, C.A.: Samail Ophiolite Plutonic Suite: Field Relations, Phase Variations, Cryptic Variation and Layering, and a Model of a Spreading Ridge Magma Chamber. J. Geophys. Res., v. 86, 1981, pp. 2593-2644.
35. Elthon, D.; Casey, J.F.; and Komor, S.C.: Cryptic Mineral Chemistry Variations in a Detailed Traverse Through the Cumulate Ultramafic Rocks of the North Arm Mountain Massif of the Bay of Islands Ophiolite, Newfoundland. Ophiolites and Oceanic Lithosphere, I.G. Gass, S.J. Lippard and A.W. Shelton, eds., Oxford, England, Blackwell, 1984, pp. 83-100.
36. Thy, P: Magmas and Magma Chamber Evolution, Troodos Ophiolite, Cyprus. Geology, v. 15, 1987, pp. 316-319.
37. Karson, J.A.; and Elthon, D.: Evidence for Variations in Magma Production Along Oceanic Spreading Centers: A Critical Appraisal. Geology, v. 15, 1987, pp. 127-131.