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ORIGIN OF THE HAWAIITES FROM THE ITCHA MOUNTAIN RANGE, BRITISH COLUMBIA

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ABSTRACT

Hawaiites are intermediate-to-mafic volcanic rocks, dominated by plagioclase, that have been erupted in continental and oceanic settings. Those from the Northern Itcha Mountain Range, British Columbia, are associated in space and time with nearly aphyric alkali olivine basalts and basanites. The hawaiites are strongly porphyritic with plagioclase phenocrysts; they usually carry plagioclase megacrysts that have a calcic overgrowth on a relatively Na-rich core. They also contain sparse, partly digested granitic xenoliths. In contrast, the type hawaiites are typically aphyric and do not carry xenoliths of any kind. The presence of granitic xenoliths in the Itcha Mountain hawaiites and their high concentrations of phenocrysts and megacrysts require a period of crystallization and probable reaction with the country rocks prior to eruption, likely in the crust. Therefore, the hypotheses proposed in the literature to explain the origin of hawaiites, either by primary melting in the mantle or solely by fractionation of basalt magma, are likely invalid for the Itcha Mountain Range rocks although they may account for the origin of the oceanic varieties. As a hypothesis for the origin of the Itcha Mountain Range hawaiites, assimilation of granitic rocks combined with olivine and augite fractionation from an alkali basalt magma meet the requirements of mass- and energy-balance calculations.

Keywords: volcanic rocks, Itcha Mountain Range, British Columbia, hawaiite, assimilation, crystal fractionation, mass balance, energy balance.

SOMMAIRE

Les hawaiites sont des roches volcaniques, variant d'intermédiaires à mafiques, à plagioclase dominant, mises en place en milieu continental ou océanique. Celles de la chaîne nord des monts Itcha, en Colombie-britannique, sont spatialement et chronologiquement associées à des roches presque aphyriques: basaltes alcalins à olivine et basanites. Les hawaiites, nettement porphyriques à phénocristaux de plagioclase, renferment communément des mégacristaux de plagioclase plutôt sodique à surcroissance calcique. Elles contiennent également de rares xénolithes granitiques partiellement digérés. Par contre, les hawaiites de la localité type sont aphyriques, sans nul xénolithe. La présence, dans les hawaiites des monts Itcha, de xénolithes granitiques ainsi que l'abondance des phénocristaux et mégacristaux impliquent une période pré-éruptive de cristallisation, voire de réaction avec les roches encaissantes, et ce, vraisemblablement dans la croûte. Les hypothèses émises dans la littérature pour expliquer la formation des hawaiites, soit par fusion primaire dans le manteau ou par fractionnement d'un magma basaltique, paraissent invalides dans le cas des hawaiites des monts Itcha quoiqu'elles puissent expliquer les hawaiites océaniques. Notre hypothèse sur l'origine des hawaiites des monts Itcha, assimilation de roches granitiques avec fractionnement d'olivine et d'augite du magma basaltique alcalin, satisfait aux exigences du calcul des bilans de masse et d'énergie.

(Traduit par la Rédaction)

Mots-clés: roches volcaniques, monts Itcha (Colombie-britannique), hawaiite, assimilation, fractionnement de cristaux, bilan de masse, bilan d'énergie.

INTRODUCTION

A hawaiite is defined as a rock with a moderate to high color index, usually of basaltic habit, with modal and normative andesine, and with Na_2O:K_2O greater than 2:1 (Macdonald 1960). Rocks that fit this definition occur in both oceanic (*e.g.*, Hawaii, the type locality) and continental regions (Best & Brimhall 1974, Bevier 1978, Nicholls *et al.* 1982). Hypotheses concerning the origin of these rocks include derivation by crystal fractionation from an alkali olivine basalt parent (Macdonald 1968, Bevier 1978) and by direct partial melting of mantle rocks (Best & Brimhall 1974). In this paper we examine the following hypotheses for the origin of a group of hawaiites from western Canada: (1) derivation by direct partial melting of mantle rock, (2) derivation by crystal fractionation from a parental basaltic or basanitic magma, (3) derivation by assimilation of granitic material in a basaltic or basanitic magma, and (4) derivation by a combination of these processes. The viability of these hypotheses is tested against petrographic observations and calculations of mass and energy balance. The data are most compatible with the last hypothesis, crystal fractionation and assimilation combined.

The hawaiites occur in the Itcha Mountain Range of south-central British Columbia, where Quaternary volcanism has produced cinder cones and lava flows on older Tertiary volcanic rocks (Fig. 1). The youngest rocks are hawaiites, alkali olivine basalts and basanites. A basanite (IM-2) and three alkali olivine basalts (IM-11, IM-18 and IM-23) were selected as the most likely representatices of primary magmase possibly parental to the hawaiites (Nicholls *et al.* 1982). These rocks are basic and nearly aphyric, with less than 10% phenocrysts, and have Sr isotope ratios less than 0.704. Olivine is the predominant and

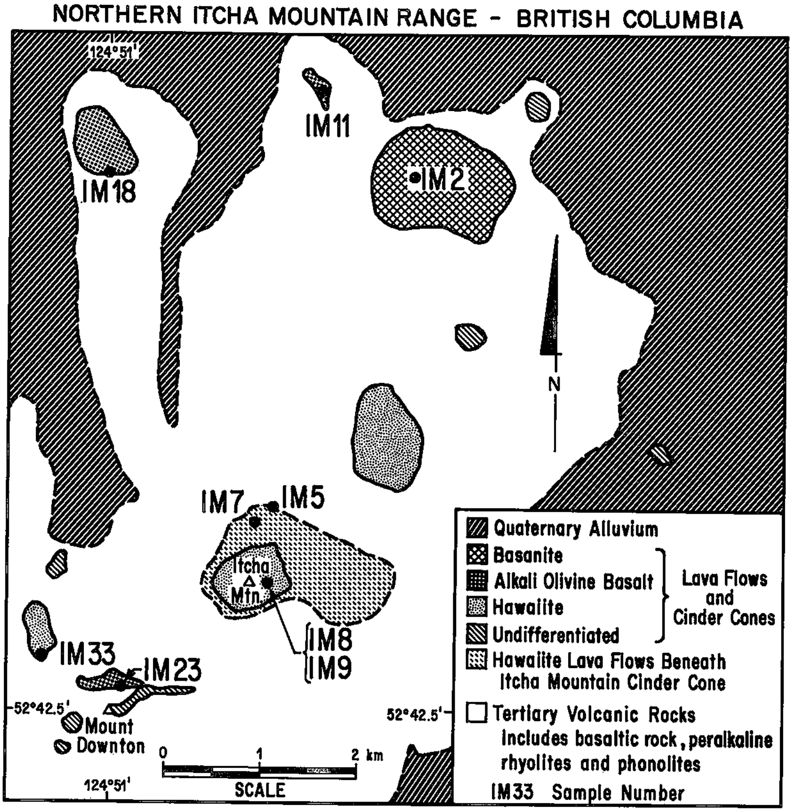

Fig. 1. Map of the Northern Itcha Mountain Range, British Columbia, showing the distribution of Quaternary cinder cones and lava flows.

ubiquitous phenocryst in both rock types, whereas plagioclase and augite are sporadically present as phenocrysts (Table 1). Although modal amounts vary, the groundmass mineralogy of each of these rocks includes olivine, augite, plagioclase and Fe-Ti oxides. In addition, the basanites carry minor amounts of groundmass leucite, rare groundmass nepheline and lherzolite xenoliths. The latter are probably of mantle origin (Nicholls *et al.* 1982). Salient chemical and petrographic features of these postulated parental magmas are given in Table 1.

TABLE 1. PETROGRAPHIC AND CHEMICAL FEATURES OF POSSIBLE PARENTAL MAGMAS TO THE ITCHA MOUNTAIN RANGE HAWAIITES

	Basanite IM-2	Alkali Olivine Basalt IM-11	IM-23	IM-18	Average
SiO_2	46.10	49.59	47.39	49.40	48.79
TiO_2	3.05	2.14	2.89	2.34	2.46
Al_2O_3	14.16	15.12	14.79	14.32	14.74
FeO	12.52	11.70	12.20	12.47	12.13
MgO	9.67	8.31	8.68	8.73	8.57
CaO	9.11	7.42	8.64	8.31	8.13
Na_2O	3.87	3.57	3.82	3.55	3.64
K_2O	1.51	2.15	1.59	0.88	1.54
Phenocryst Mineralogy (Volume %)					
Oliv	3.6 2.3*	2.2	3.0	1.9	
Plag	1.1 0.0	1.2	1.6	0.0	
Augite	0.0 0.0	0.0	3.3	0.8	

Analyses from Nicholls et al. (1982), recalculated to 100% with total iron as FeO.

*Two samples from the same cinder cone.

Petrography and Chemistry of Hawatiites

The hawaiites from western Canada are typically porphyritic, often extremely so (Bevier 1978, Nicholls *et al.* 1982), and thus differ from the typically aphyric Hawaiian varieties (MacDonald 1949, p. 1549). Comparison of modal compositions of Hawaiian and Itcha Mountain Hawaiites (Table 2) shows thate the latter carry more olivine and plagioclase phenocrysts. Phenocrysts of olivine occur in four of the five specimens of Itcha Mountain hawaiite, and augite phenocrysts occur in one, whereas the Hawaiian sample described in Table 2 has neither phenocrysts of olivine nor of augite. In addition, plagioclase megacrysts (An^{35} – An^{50}) occur in several of the Itcha Mountain hawaiites. These are more An-poor

TABLE 2. CHEMICAL AND PETROGRAPHIC FEATURES OF ITCHA MOUNTAIN RANGE HAWAIITES

	ITCHA MOUNTAIN RANGE					HAWAIIAN ISLANDS	
	IM-33	IM-9	IM-7	IM-5	IM-8	C-72	Average
SiO_2	49.49	48.74	49.14	49.10	49.05	49.12	49.02
TiO_2	2.52	3.09	3.01	3.01	3.10	2.68	3.48
Al_2O_3	15.73	17.06	17.54	17.58	17.75	19.81	16.27
FeO	11.12	11.81	11.46	11.41	11.56	10.66	12.29
MgO	6.75	4.85	4.70	4.63	4.74	4.49	4.91
CaO	8.40	8.03	8.18	8.17	7.93	6.69	8.19
Na_2O	4.25	4.66	4.35	4.43	4.24	4.69	4.30
K_2O	1.74	1.76	1.62	1.67	1.63	1.86	1.54
Modes (Volume %)							
Phenocrysts							
Oliv	4.0	1.6	1.6	0.9	0.7	0.0	
Plag	4.2[5]	7.7	9.8	12.9	14.8[6]	0.0	
Augite	2.9	0.0	0.0	0.0	0.0	0.0	
Groundmass							
Oliv	12,8	12.7	10.3	11.3	16.9	7.7	
Plag	51.3[7]	50.1	54.4	47.6	41.6	56.2[3]	
Augite	9.4	4.9	13.9	15.3	5.5	18.6	
Opaque	15.0	22.3	9.2[1]	9.5	18.0[2]	16.7	
Undt	0.4	0.7	0.8	2.5	2.5	0.8[4]	

1. Includes 0.6 microphenocrysts
2. Includes 0.9 microphenocrysts
3. Includes 3.0 untwinned feldspar
4. Includes 0.5 glass
5. Includes 2.7 megacrysts
6. Includes 10.8 megacrysts
7. Includes minor nepheline

Analyses of Itcha Mountain Range rocks from Nicholls et al. (1982). Hawaiian Island analyses from Macdonald & Katsura (1964, C-72) and Macdonald (1968, Average). Totals recalculated to 100% with total iron as FeO.

than the phenocryst and groundmass plagioclase and have more An-rich than their cores, suggesting that the cores of the megacrysts crystallized at a higher pressure the mantles and phenocrysts. In one sample (IM-33), there is minor groundmass nepheline.

Of petrographic significance in the Itcha Mountain Range hawaiites are sparse, partly digested granitic xenoliths. These fragments consist of quartz, microcline and minor amounts of opaque minerals in clusters that probably are relics of amphibole or biotite.

The major and minor elements in the Itcha Mountain Range hawaiites are within the ranges of concentration found in hawaiites from the Island of Hawii (Macdonald & Katsura 1964). Compared to the average for the Hawaiian rocks, the Itcha Mountain hawaiites are slightly richer in K_2O and poorer in TiO_2 (Table 2) and P_2O_5 (*cf.* Macdonald 1968, Table 8; Nicholls *et al.* 1982, Table 2).

ASSIMILATION AND CRYSTAL FRACTIONATION HPOTHESES

The porphyritic nature of the Itcha Mountain hawaiites indicates a period of intratelluric crystallization during which the megacrysts and phenocrysts formed. In addition, the partial digestion of xenoliths requires some interaction between the original magma and the country rock, most probably within the crust. These features likely invalidate the hypotheses that suggest formation of hawaiite directly as a primary melt of mantle material or as a product solely of crystal fractionation of basaltic magma. We are left with the hypotheses of assimilation of granitic material alone or in combination with crystal fractionation as the mechanisms for the formation of the hawaiites. Such hypothesee postulate an initial or parental magma; one of the problems in devising tests of these hypotheses is identifying the nature of the initial magma.

The usual procedure is to postulate a more basic rock as representative of the parental magma. The case for the correctness of the choice is considered strengthened if such rock types form part of the volcanic complex. In the Itcha Mountain Range, alkali olivine basalts and basanites are candidates for parental magmas; their chemical characteristics are given in Table 1. The batch of magma that was the immediate antecedent of a differentiate is destroyed by the differentiation process. The best we can expect is a sample, in the form of a body of rock, of the initial magma that segregated prior to differentation. Much of the literature, at least in our view, implies that such samples are avaiable. Considering the state of knowledge of the mechanisms of magma movement in the outer reaches of the earth, this is an unsupported assumption. An alternate possibility involves the production of multiple batches of similar magma. Some batches could differentiate at depth, whereas other could come to the surface as lava flows. Consequently, our postulated magma compositions should be similar to those in Table, but we would not necessarily expect an exact match. In addition, the variation in the compositions in Table 1 can provide a measure of whether the postulated magma composition is sufficiently dissimilar from the listed compositions to warrant rejection of the differentiation hypothesis.

Specifically, mass-balance calculations use a least-squares technique to estimate the amounts of added or subtracted phases required to change the composition of one magma into another (*e.g.*, Chayes 1968, Bryan *et al.* 1969, Stormer & Nicholls 1978). Once these estimates have been calculated, the original equations can be manipulated to give the composition of an initial magma that is an exact fit to the equations with the estimated amounts of added or subtracted phases. In this paper, we will call this the perfect fit or ideal magma composition; it is this composition that is to be compared with the data in Table 1.

The results of a particular mass-balance calculation can be graphically summarized as in Figure 2. The dots mark the concentrations of the indicated oxides in the average basalt composition (Table 1). The intersection of the vertical line labeled I and the X axis marks the concentration of silica in the perfect fit. The concentrations of the other oxides for a perfect fit are given by the intersections of the approximately horizontal lines with line I. The distances

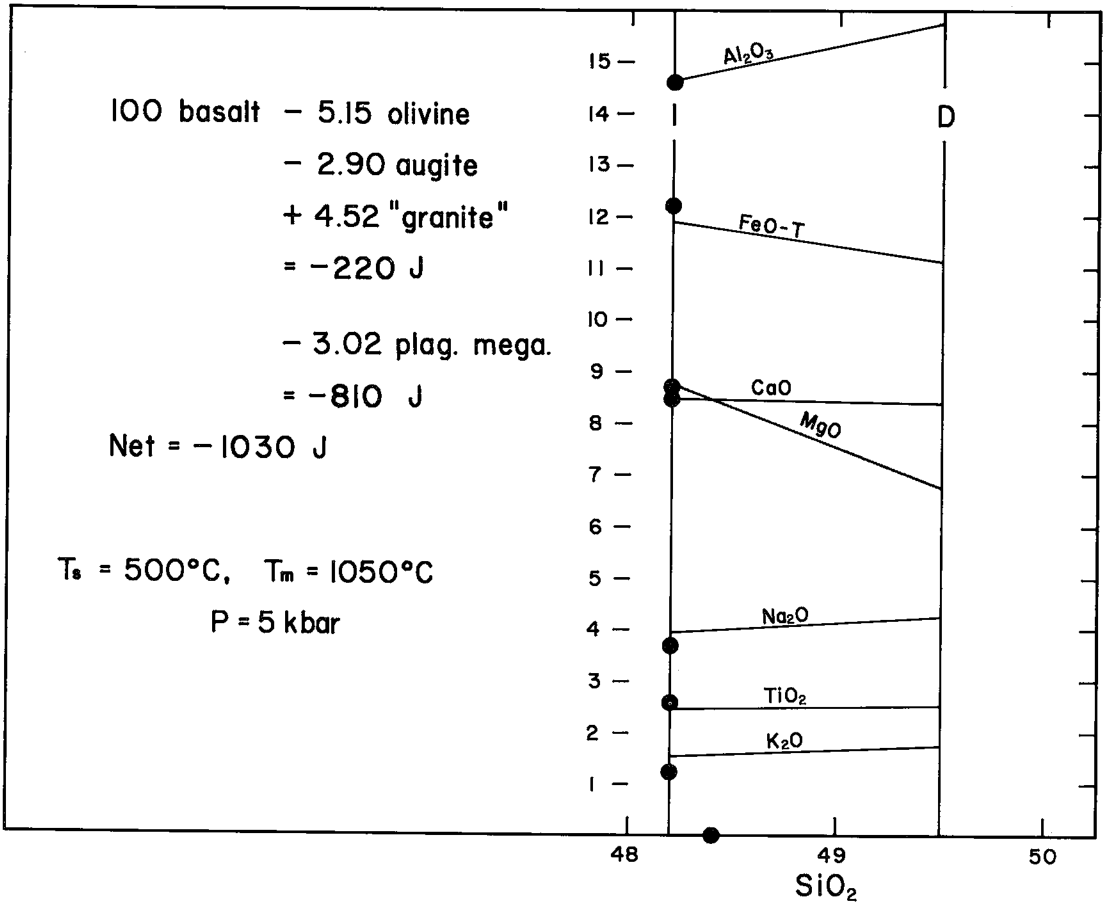

Fig. 2. Diagram showing the calculated energy- and mass-balance for deriving the least phyric hawaiite (IM-33) from the average Itcha Mountain Range basalt composition by fractionation of olivine and augite and assimilation of Coast Range granodiorite ("granite"). Concentrations in weight percent.

between the dots and the intersections are a measure of the lack of fit to the differentiation model. The greatest variation within the possibly parental compositions (Table 1) occurs with silica, which has a maximum deviation from the mean of 1.4%. If the silica residual between the perfect fit and the model composition (in this case, the average basalt composition) is greater than this number, we reject the differentation hypothesis under discussion. The other oxides generally contribute smaller residuals. To take these into account, we use the following criteria from mass-balance calculations for rejecting a particular differentiation process: if the sum of the squares of the residuals (S^2) is less than 2.0, do not reject on the basis of mass balance; if $2.0 < S^2 < 3.0$, the test is equivocal and no conclusion can be reached; if $S^2 > 3.0$, reject the hypothesis. These numbers were chosen as approximations to the sum of squares of the variations between the oxides constituting the compositions listed in Table 1.

Beyond the fundamental impossibility of transferring heat from cool country rocks to hot magmas, the amount of knowledge about the energy budgets of magmas is meagre. Consequently, the criterion for rejection on the basis of energy-balance calculations is simple: if heat is required by the magma from the country rocks in order for the process to occur, reject the hypothesis. The uncertainties in the energy-balance calculations are discussed by Nicholls & Stout (1982) and suggest that any balance with an absolute value greater than 100 J per 100 g of initial magma is significantly different from zero. In the following discussion, amounts crystallized or assimilated according to the various mass-balance calculations are quoted as percentages of the inital mass of magma. In other words, the amounts are

TABLE 3. SUMMARY OF RESULTS OF MASS- AND ENERGY-BALANCE CALCULATIONS

Hawaiite	Mass Balance Initial Magma	S^2	Energy Balance J/100 g Initial Magma	Differentiation Mechanisms Xlf		Assim
IM-33	IM-23	2.48	13250			15%
	IM-23	0.16	5270	4% ol	2% au	10%
	IM-2	1.25	11560	6% ol		17%
	Average	0.43	-1030	5% ol	3% au	5%
IM-9	IM-23	0.12	-10660	8% ol	10% au	2%
	IM-2	6.76		13% ol		6%
IM-7	IM-23	0.25	-10080	9% ol	9% au	3%
	IM-2	6.48		14% ol		8%
IM-5	IM-23	0.20	-10670	9% ol	9% au	3%
	IM-2	6.48		14% ol		8%
IM-8	IM-23	23.34				12%
	IM-2	8.00		14% ol		7%
	Average	0.15		see text		
	IM-23	0.35	-11390	9% ol	11% au	3%

Abbreviations are: ol = olivine, au = augite, Xlf = phases fractionated and their percentages, Assim = percent assimilated. In all cases the assimilated material is granodiorite in composition. A negative energy-balance indicates that heat is released to the country rocks.

in mass units relative to 100 mass units of initial magma.

A complete summary of the tests of several hypotheses for the derivation of hawaiites is given in Table 3. In the ensuing discussions, we will concentrate on hypotheses for the derivation of IM-33, the hawaiite with the smallest concentration of megacrysts, and IM-8, the hawaiite with the largest amount. If a hypothesis cannot be disproved for these two samples, generally it cannot be disproved for the other samples.

The assimilation hypothesis

The presence of partly digested granitic fragments and plagioclase megacrysts suggests that the most straightforward hypothesis for the origin of the Itcha Mountain hawaiites is assimilation of crustal material by a parental magma and concomitant crystallization of plagioclase megacrysts to supply the required energy. Because the granitic fragments in the lavas are few, small and extensively altered, it is not possible to obtain the composition of the assimilated material directly. Average compositions of granodiorite and quartz monzonite from the Coast Range batholith were used as estimates of the composition of the assimilated material (Buddington 1927).

Derivation of the least phyric hawaiite (IM-33) from one of the alkali olivine basalt compositions (IM-23) by assimilation alone gives only an equivocal fit for the mass balance; the sum of the squares of the residual is 2.48 (Table 2). To further evaluate the validity of this hypothesis, energy-balance calculations were done using the methods described by Nicholls & Stout (1982). The calculated balances of energy do not vary greatly with pressure and temperature (approximately 15 J per 100 degrees change in temperature, 1 J for every kilobar change in pressure for every gram of crystallized or assimilated material). All calculations were done for an estimated pressure of 5000 bars and an initial temperature in the assimilated material of 500°C. The initial and final temperature of the magma was estimated to be 1050°C. Owing to the lack of available thermochemical data, energy calculations for the assimilated material must be done using normative amounts of granitic material (quartz, anorthite, albite and orthoclase) in place of the actual granodiorite and quartz monzonite compositions used in the mass-balance calculations. This introduces a small error, as the normative constituents used account for only 85% of the mass of the assimilated material.

In this model, 15% granodiorite must be assimilated by the average basalt to produce the hawaiite (IM-33). The assimilation of 15% granitic material requires more than 14200 J per 100 g of initial melt. Crystallization of the 3.6% of plagioclase megacrysts actually present in the hawaiite provides only 960 J per 100 g of initial magma. The net balance of energy for this model shows that approximately 13250 J per 100 g of initial melt are required from the external surroundings. This effectively eliminates assimilation and concomitant precipitation of plagioclase megacrysts as a viable mechanism for the origin of IM-33. Because the derivation of the other hawaiites from individual alkali olivine basalt and basanite compositions by assimilation alone gives unacceptable fits to the mass balance ($S^2 > 6.0$), no further evaluations of this hypothesis by energy-balance calculations are required.

The assimilation + crystal fractionation hypothesis

Another geologically reasonable hypothesis is assimilation of crustal material combined with crystal fractionation of olivine and augite from the parental magma and concomitant crystallization of plagioclase megacrysts. Deriving the same hawaiite (IM-33) as in the previous example from the same alkali olivine basalt (IM-23) gives a very close fit to a mass balance ($S^2 = 0.16$, Table 3). Assimilation of 10% granitic material and crystallization and fractionation of olivine and augite require 6140 J per 100 g of initial melt. Crystallization of plagioclase megacrysts contributes less than 870 J per 100 g of initial magma of the required energy. Therefore, although this model is the best fit with respect to a mass balance, it has an unrealistic energy-balance as it also requires heat from an external source.

A basanite parent gives an acceptable fit to the mass balances ($S^2 = 1.25$) for the derivation of the hawaiite (IM–33) by assimilation of granodiorite and fractionation of olivine. Assimilation of 17% granitic material and crystallization of olivine require approximately 12500 J per 100 g of initial melt. Only 920 J per 100 g are released by the crystallization of plagioclase megacrysts, so that heat would again be required from the external environment (Table 3).

The same hawaiite (IM–33) can be derived from the average basalt composition with an acceptable mass-balance ($S^2 = 0.43$) and a reasonable energy-balance. The oxide plot (Fig. 2) illustrates the differences between the composition of the exact fit and the initial composition. The model requires fractionation of augite and olivine and assimilation of granodiorite. This produces approximately 220 J per 100 g of initial magma. The crystallization of plagioclase megacrysts produces another 810 J, giving a total of 1030 J of heat per 100 g of initial magma that would be lost to the surroundings.

The hawaiite under discussion contains the smallest amount of plagioclase megacrysts, approximately 3% by volume. Next we discuss the mass and energy balances for the hawaiite with the largest amount of megacrysts, IM–8, which contains approximately 11% megacrysts. This hawaiite superficially has an excellent mass-balance with the average basalt composition as parent (Table 3). The unrestrained least-squares calculation, however, requires the fractionation of granodiorite rather than its assimilation to reach the minimum sum of the squares of the residuals. Consequently, the average basalt composition cannot act as a suitable parent for IM–8. The hawaiite can, however, be derived from one of the alkali olivine basalt compositions (IM–23) by fractionation of olivine and augite and assimilation of granitic materials ($S^2 = 0.35$). This produces approximately 8310 J of heat. Crystallization of 11.4% plagioclase megacrysts produces an additional 3080 J, giving a total of 11390 J per 100 g of initial melt that must be lost to the environment. Hence, this model, *i.e.*, the derivation of IM–8 from a basalt parent (IM–23), cannot be ruled out by either mass- or energy-balance calculations since heat is released to the environment; it thus is a viable hypothesis. The basanite composition cannot be representative of the parental magma for this hawaiite (IM–8) because derivation of this hawaiite from the parental basanite magma is eliminated by mass-balance calculations ($S^2 = 8.0$, Table 3).

SUMMARY

In the assimilation hypothesis, we find that the hawaiites cannot be derived from either the average basalt composition or basanite composition by assimilation alone. Mass-balance calculations eliminate the basanite composition as a parental magma and provide, at best, equivocal fits for the basalt parent. Energy-balance calculations eliminate the basalt as a parental composition since the assimilation of granitic material requires more heat than can be provided by the crystallization of the megacrysts.

The remaining hypothesis, combined assimilation and crystal fractionation, can be eliminated for some compositions but cannot be disproved for others. Deriving the hawaiite with the fewest megacrysts (approximately 3% in IM–33) from a particular basalt parent requires assimilation of 10% granitic material and crystallization of approximately 10% augite, olivine and plagioclase, a ratio of one to one in assimilated to crystallized masses. This model gives an excellent mass-balance, but heat is required from the surrounding rocks, an unlikely source. Derivation of IM–33 from a basanite parent can be accomplished by assimilation of 17% granitic material and crystallization of approximately 10% olivine phenocrysts and plagioclase megacrysts, a ratio of approximately two to one. This would again require energy from an external source, which invalidates the hypothesis. The most likely hypothesis for the origin of IM–33 involves a basalt with approximately the average composition. Assimilation of approximately 5% granitic material, fractionation of olivine and augite and crystallization of plagioclase megacrysts, with the total amount crystallized being approximately 11%, gives a good mass-balance. The ratio of assimilated to crystallized material is approximately one to two, which provides a small amount of excess heat for release to the external surroundings.

Mass-balance calculations eliminate both the basanite and the average basalt compositions as parent magmas for the hawaiites with the largest amounts of plagioclase megacrysts (approximately 11% in IM–8). However, these hawaiites can be derived from a particular alkali olivine basalt parent (IM–23). The model requires approximately 3% assimilation of granitic material and crystallization of approximately 30% olivine, augite and plagioclase, a ratio of 1 to 10 in assimilated to crystallized masses. The energy-balance calculations show that this model would release approximately 11390 J per 100 g of initial magma to the surrounding rocks.

A rough estimate of the effect of the calculated amounts of heat released by these latter models can be made. Fyfe *et al.* (1978) cited a value of approximately 2300 J of heat as the energy required per gram of H_2O released during metamorphic dehydration reactions. Applying this value, we calculate that only a very thin rind would be produced by the release of 600 J per 100 g of initial melt, but a thermal anomaly with a volume equivalent to that of the initial magma could be produced by the release of 8000 J per 100 g of initial melt.

CONCLUSIONS

A ratio of assimilated material to crystallized material of more than one to two will generally require heat from an external source. Energy calculations allow further evaluation of hypotheses and place additional constraints on otherwise acceptable mass-balance calculations. Using only mass-balance calculations, we find that some Itcha Mountain Range alkali olivine basalts and basanites will not produce any of the associated hawaiites. Evaluation of the energy balance as well shows that: 1) the average basalt composition will not produce all of the hawaiites, and 2) the basanite compositions are not suitable parental compositions for any of the hawaiites. Therefore, if the hawaiites are derivatives of primary magmas, they are derived from alkali olivine basalt magmas that were variable in composition. The derivatives likely formed by combined processes of assimilation of crustal material and crystal fractionation of olivine and augite with concomitant crystallization of plagioclase megacrysts. Available data suggest that chemically heterogeneous magmas gave rise to chemically heterogeneous derivative lavas with different amounts of heat released to the external environment.

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