

## Igneous layering in a dacite: on the origin and significance of Layer Cake Mountain, Kelowna, B.C., Canada

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### ABSTRACT

A Tertiary, dacitic volcanic land-form in Kelowna, British Columbia, shows layering that has not been recognized elsewhere. Layering is expressed as thin (0.5 m) layers separated by thick (4.5 m) layers exposed along a weathered fault scarp. The major elements show that both thick and thin layers are dacitic and geochemically very similar. Trace element modelling indicates that thin layers formed from thick layers via crystal fractionation involving removal of plagioclase, biotite and magnetite in the proportions 75:20:5, and with only 12% fractionation. The thin layers represent segregation veins generated during crystallization of the dacite. They formed when the crystal mush at the bottom of the upper crust successively, thermally contracted, fractured and foundered, siphoning evolved interstitial liquid from the mush into the horizontal crack. Cooling of the segregation veins led to further fracturing. Later, fluids following these fractures altered the thin layers and precipitated secondary carbonate minerals. The altered thin layers weather preferentially, thus visually accentuating the small primary chemical differences between thick and thin layers. The scale of layering, mode of formation and differentiation mechanisms appear different from those in felsic magma chambers and it is unclear how common this phenomenon is. However, similar layering is more easily identified and commonly developed in mafic lava flows.

**KEYWORDS:** igneous layering, dacite, fluids, differentiation, Kelowna, Canada.

### Introduction

CHEMICAL layering is not often reported from individual lava flows but in recent years a number of studies have indicated that it is not uncommon in basaltic flows (Helz, 1980, 1987; Greenough and Dostal, 1992*a,b*). Layer Cake Mountain (Kelowna, B.C.; Fig. 1) represents one of the most spectacular examples of layering in a volcanic unit (possibly a lava flow) anywhere (Fig. 2). What makes it particularly impressive is that the unit has a dacitic composition. To the authors' knowledge, there are no discussions of layering in these types of rocks in the literature.

Layer Cake Mountain is one of the most

prominent landmarks in the Kelowna area and discussions with numerous geologists revealed that many have pondered its origin. If each layer represents an individual lava, what processes operated to maintain such uniform flow thicknesses? According to Church (personal communication, 1997), around 1961 Little had realized that the entire hill represents a single cooling unit. He facetiously proposed to Geological Survey of Canada colleagues that the tilted layers represent threads on a 'Geotectobolt' that screwed its way to the surface! This work reveals that commonplace primary (igneous) and secondary processes have combined to produce the prominent layering at Layer Cake Mountain.

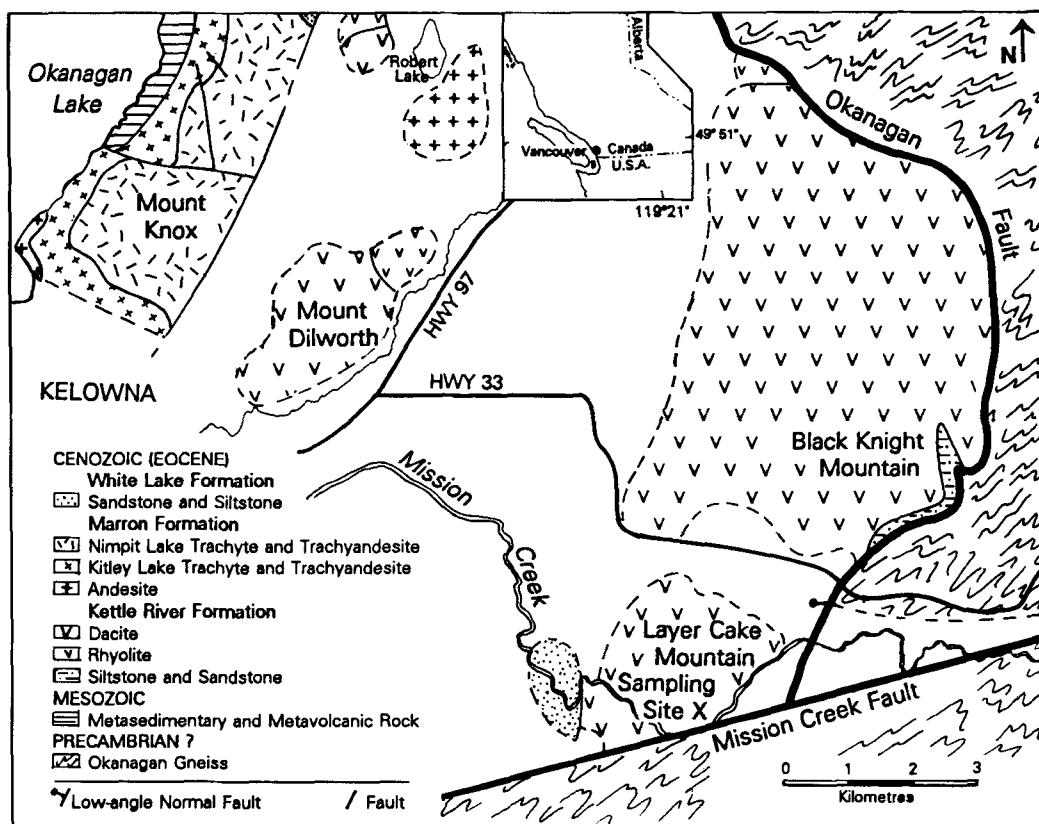


FIG. 1. Map showing geology of the eastern portion of the Kelowna Tertiary basin and the location of Layer Cake Mountain. Geology modified from Church (1981), Tempelman-Kluit (1989), Greenough and Roed (1995).

### Geology and sampling information

Layer Cake Mountain is located at the south-eastern, fault bounded edge of a Tertiary (Eocene) volcano-sedimentary basin at Kelowna (Figure 1). Similar sequences, thought to be related to caldera formation and infilling, occur at numerous localities throughout south-central British Columbia (Church, 1973, 1982). Lithologic and geochemical similarities to rocks of known stratigraphic position in the Kelowna basin indicate Layer Cake Mountain belongs in the Kettle River Formation. Other volcanic rocks from the basin produced K/Ar dates ranging from 52.9 to 44.2 Ma (Church, 1980, 1981).

The hill is bounded on the south by a steep ENE–WSW trending fault (Mission Creek Fault) that crosses the valley and offsets a regional low-angle normal fault (Okanagan Fault) that probably underlies the unit (Greenough and Roed, 1995).

Movement on these faults may be responsible for extensive folding and deformation that helps define the depression on the left-hand (western) side of Fig. 2, although layering in most of the hill is subhorizontal with a 5–10° degree dip toward the WNW.

Approximately 28 layers, which are laterally continuous for hundreds of metres, occur in the cliff face (Fig. 2). Crude columnar jointing locally crosses layers indicating that the rocks represent a single cooling unit. The lower eight layers, those accessible without climbing gear (Fig. 3), consist of thick massive layers averaging 460 cm thick separated by thin, preferentially eroded layers typically 50 cm thick. Locally, 'glassy' fingers form ~10 cm diapiric structures that originate at the upper edge of thick layers and intrude the thin layers. To test for variations within individual layers and between layers over



FIG. 2. Photograph looking NNW showing Layer Cake Mountain.

the accessible portion of the unit, layers 1, 2, 3, 7 and 8 were sampled in detail (Fig. 3).

### Petrography, mineralogy and sample descriptions

Thick and thin layer samples show a fine-grained ( $\leq 0.1$  mm) 'felted' texture consisting of feldspar microlites, Fe-Ti oxides, ferromagnesian minerals and devitrified glass. Plagioclase ( $\sim 15\%$ ,  $\leq 6$  mm) and biotite ( $< 5\%$ ,  $\leq 0.5$  mm) form phenocrysts whereas Fe-Ti oxides form microphenocrysts ( $\leq 1\%$ ,  $\leq 0.2$  mm). Some fine-grained samples show a weak trachytic texture with alignment of plagioclase and serrated Fe-Ti oxides. Biotite is usually altered and in some thin layer samples partly replaced by carbonate. Microcrystalline carbonate also pseudomorphs and replaces the matrix in some thin layer samples.

Plagioclase phenocrysts are largely unaltered in both thick and thin layer samples. Analyses were done using the Dalhousie University (Halifax, Canada) JEOL Superprobe 733 microprobe running wavelength dispersive spectrometers, a focused ( $\sim 1-2$   $\mu\text{m}$ ) electron beam, an acceler-

ating voltage of 15 kV, a count time of 30 s and mineral standards for calibration. Compositions range from  $\text{An}_{55}$  to  $\text{An}_{35}$ , average  $\text{An}_{45}$ , and show no statistical difference between thick and thin layer samples (Fig. 4).

### Analytical data

#### Methods

Weathered or altered surfaces were removed from samples prior to crushing and powdering in a tungsten-carbide mill. The major elements were determined by X-ray fluorescence (XRF) on fused glass pellets at Memorial University of Newfoundland. Precision and accuracy are  $\pm 2\%$  or better. Trace elements determined by XRF on pressed powder pellets (following Longerich, 1995) were run with geological reference materials indicating precision and accuracy better than  $\pm 5\%$  for Cr, Ni, Sc, V, Zn, Ga, Zr and Nb,  $\pm 10\%$  for Cu, S, Cl and As, and  $\pm 20\%$  for Pb. Precision and accuracy suffer when concentrations approach detection limits (e.g. some Cr and Ni analyses). The rare earth elements (*REE*), Y, Rb, Sr, Ba, Hf and Th were

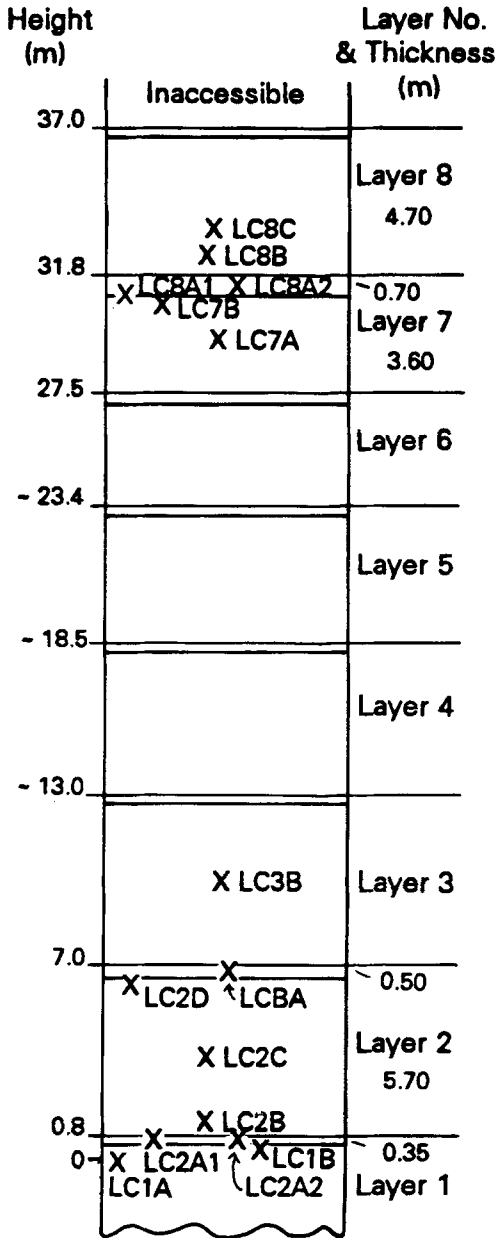


FIG. 3. Stratigraphic section showing layer thicknesses and the location of samples from the accessible portion of the hill.

determined using a sodium peroxide sinter collection procedure with analysis by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS; Longerich *et al.*, 1990). In-run refer-

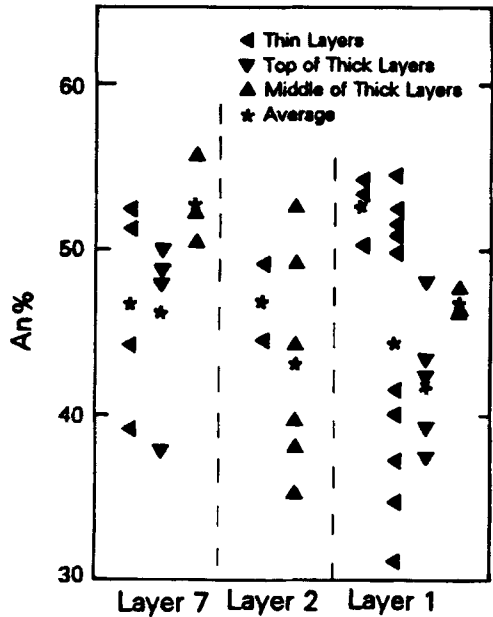


FIG. 4. Plots of the An content of plagioclase phenocrysts determined using the electron microprobe. Analyses come from the samples (left to right): Layer 7, LC8A1, LC7B, LC7A; Layer 2, LC3A, LC2C; Layer 1, LC2A1, LC2A2, LC1B, LC1A).

ence materials indicate precision and accuracy better than 4%.

Results

Major element and trace element data (Table 1) show that various elements, particularly the alkali and alkaline earth metals exhibit a relationship with loss on ignition (LOI; Fig. 5). Trends are established by three thin layer samples with high LOI values (>8 wt.%; LC2A1, LC8A1 and LC8A2, Table 1; Fig. 5).

Major element compositions of the thick layer samples and the two relatively unaltered thin layer samples (LC3A and LC2A2) are all similar (Table 1). Thus, the between-sample similarity of plagioclase compositions is not surprising (Fig. 4) and based on normative mineralogy (Irvine and Baragar, 1971) they are all dacites. Nevertheless, various trace elements serve to distinguish the thin layer samples from all thick layer samples (Fig. 6) and Fe<sub>2</sub>O<sub>3</sub>, some REE, U, Hf and Tl (for example) tend to separate samples from the top, middle and bottom of thick layers.

TABLE 1. Major element and trace element concentrations in Layer Cake Mountain samples

	LC8C	LC8B	LC8A2	LC8A1	LC7B	LC7A	LC3B	LC3A	LC2D	LC2C	LC2B	LC2A1	LC2A2	LC1B	LC1A
Group <sup>2</sup>	3	2	5A	5A	4	3	3	5	4	3	2	5A	5	4	3
Layer <sup>3</sup>	8	8	7	7	7	7	3	2	2	2	2	1	1	1	1
Height <sup>4</sup>	33.5	32.5	31.45	31.2	30.9	29.4	10	6.75	6.1	3.65	1.2	0.7	0.7	0.45	0.1
SiO <sub>2</sub>	68.93	68.23	61.96	60.27	69.24	69.23	69.25	66.83	70.44	69.37	68.67	64.95	70.15	70.24	69.18
TiO <sub>2</sub>	0.58	0.58	0.83	0.59	0.58	0.57	0.57	0.63	0.57	0.57	0.57	0.69	0.58	0.58	0.57
Al <sub>2</sub> O <sub>3</sub>	14.46	14.72	19.94	14.5	14.57	14.34	14.61	16.76	14.67	14.39	14.86	17.88	14.82	14.5	14.51
Fe <sub>2</sub> O <sub>3</sub>	3.61	3.63	4.72	5.26	3.01	3.41	3.59	2.69	2.21	3.29	3.89	2.82	2.13	2.44	3.29
MnO	0.03	0.03	0.04	0.26	0.02	0.04	0.05	0.01	0.02	0.05	0.06	0.02	0.03	0.02	0.04
MgO	0.92	1	3.18	1.2	0.88	0.93	0.76	0.58	0.45	0.94	0.48	0.64	0.26	0.28	0.68
CaO	2.59	2.42	3.85	9.54	2.47	2.65	2.77	2.75	2.62	2.48	2.53	5.01	3	2.91	2.63
Na <sub>2</sub> O	3.31	3.25	2.65	2.7	3.1	3.3	3.23	2.96	3.27	3.32	3.16	3.74	3.26	3.3	3.17
K <sub>2</sub> O	3.5	3.74	1.49	3.46	3.29	3.43	3.37	4.45	3.37	3.42	3.74	1.87	3.57	3.34	3.46
P <sub>2</sub> O <sub>5</sub>	0.22	0.21	0.29	0.22	0.21	0.2	0.2	0.23	0.2	0.2	0.21	0.23	0.21	0.2	0.2
Total	98.15	97.81	98.95	98	97.38	98.1	98.41	97.89	97.82	98.03	98.17	97.86	98.01	97.81	97.74
LOI <sup>1</sup>	1.7	2.04	14.39	8.58	2.25	1.6	2.7	4.08	2.21	2.99	2.47	8.26	1.35	1.62	3
Mg# <sup>1</sup>	0.36	0.38	0.6	0.33	0.39	0.38	0.32	0.32	0.31	0.39	0.21	0.33	0.21	0.2	0.31
Cl	258	326	3406	521	220	228	243	269	197	190	234	301	191	262	214
S	56	173	101	943	251	57	52	42	35	54	103	129	55	57	47
As	0.52	n.d.	n.d.	4.1	10	3.7	4.9	1.7	9.2	5.1	n.d.	n.d.	1.4	0.66	n.d.
Li	25.3	28.3	15.6	15.9	23.8	24.2	26.3	13.9	26.1	22.4	27.2	10.4	17	19.1	21.9
Rb	74.5	78.5	13.2	51.3	67.6	70.9	69.7	80	68.2	70.3	74.7	56.9	67.9	60.6	71.8
Cs	0.838	0.959	0.586	0.372	0.384	0.796	0.59	0.318	0.634	0.904	0.849	1.84	0.351	0.282	0.635
Sr	345	322	471	383	333	343	300	319	336	313	340	568	409	382	294
Ba	1111	1229	1540	1595	1128	1150	1160	1532	1093	1098	1268	2112	1194	1242	1057
La	30.6	31.5	40.1	36.2	31.3	30.5	28.9	31.3	30.4	29.8	32.9	29.7	33.1	31.5	31.1
Ce	65.3	66.5	87.6	70.6	64.8	64	60.4	64.8	64.8	63.9	69.5	64.5	70.2	65.6	65.3
Pr	7.9	8.02	10.6	8.54	7.98	7.69	7.18	7.86	7.81	7.57	8.09	7.71	8.32	7.96	7.68
Nd	30	30.5	38.8	33.4	29.7	30.1	27.4	30.6	30.1	29.1	31.4	29.9	31.5	30.1	30
Sm	5.79	5.83	7.29	6.22	5.87	5.58	5.43	6.24	5.81	5.67	6.18	5.95	6.28	5.89	5.7
Eu	1.11	1.12	1.27	1.3	1.07	1.05	1.1	1.16	1.14	1.06	1.09	1.2	1.13	1.08	1.07
Gd	5.05	4.93	6.05	5.47	4.67	4.62	4.58	5.2	4.71	4.87	5	4.74	5.29	5.11	5.08
Tb	0.737	0.711	0.928	0.847	0.691	0.698	0.682	0.797	0.675	0.714	0.752	0.727	0.815	0.734	0.734
Dy	4.36	4.42	5.4	5.16	4.32	4.1	4.18	4.97	4.26	4.31	4.35	4.4	4.68	4.63	4.44
Ho	0.865	0.87	1.11	1.03	0.883	0.854	0.831	1.04	0.844	0.858	0.895	0.862	0.988	0.935	0.866
Er	2.52	2.64	3.26	3.2	2.56	2.51	2.42	3.08	2.47	2.57	2.66	2.43	2.82	2.82	2.54
Tm	0.375	0.387	0.491	0.46	0.381	0.362	0.355	0.469	0.355	0.396	0.395	0.368	0.435	0.424	0.38
Yb	2.5	2.45	3.16	3	2.31	2.39	2.31	3.32	2.36	2.52	2.46	2.55	2.93	2.9	2.49
Lu	0.375	0.39	0.485	0.472	0.389	0.365	0.357	0.525	0.363	0.37	0.397	0.389	0.408	0.435	0.369
Y	23.7	23.5	30	29.7	22.7	22.8	21.9	29.2	21.3	22.8	23	23.3	25.2	24.8	22.5
Zr	249	248	303	239	250	248	243	277	250	250	254	283	264	245	242
Hf	6.62	6.75	7.85	6.68	6.44	6.5	6.43	7.38	6.65	6.5	6.96	7.74	6.91	6.62	6.55
Nb	14.4	14.8	17.1	13	14.1	14.2	14.6	16.3	14.7	14.2	14.5	16.3	14.9	15.1	14.6
Ta	1.91	1.86	1.07	1.45	2.13	2.06	2.15	1.3	1.87	1.49	2.06	1.4	3.31	2.46	2.12
U	1.9	2.03	1.36	2.4	2.13	1.99	1.81	2.19	2.01	1.76	1.96	1.5	2.36	2.07	1.96
Th	5.47	5.55	7.36	5.52	5.66	5.51	5.57	6.25	5.73	5.42	6.02	6.4	6.08	5.93	5.95
Pb	11.3	11.5	14.7	15	10.8	11.3	11.8	15	11.3	11.2	14.3	13.9	15.7	15.6	12
Tl	0.435	0.47	0.101	0.357	0.377	0.424	0.402	0.523	0.415	0.434	0.522	0.318	0.462	0.368	0.414
Zn	33	33	70	44	31	30	33	22	15	66	42	81	55	69	30
Cu	10	9	9	9	12	10	8	9	12	9	9	9	13	9	9
Mo	2	2	0.78	3.3	2	2	2.4	1.7	1.6	2.3	2.4	1.5	2.6	2.2	2.3
Ga	16	16	16	13	16	14	17	17	16	17	15	16	19	17	16
V	71	75	91	72	72	71	73	78	77	82	75	89	73	66	78
Sc	5	5	8	16	9	6	7	8	10	8	9	12	8	11	10
Cr	13	13	8	6	9	8	6	11	8	15	8	12	16	11	8
Ni	3	2	2	3	3	2	3	n.d.	3	1	2	0.2	0.2	2	3

<sup>1</sup> Major element oxides in wt.% volatile free with total Fe as Fe<sub>2</sub>O<sub>3</sub>, LOI = wt. % loss on ignition. Mg# = Mg/(Mg + 0.9\*Fe) atomic. Trace elements in ppm. n.d.: Not detected

<sup>2</sup> Group Numbers: 2 = Bottom of thick layers; 3 = Middle of thick layers; 4 = Top of thick layers; 5 = Thin layers; 5A = Altered thin layer samples.

<sup>3</sup> Layer refers to the layers in the stratigraphic column (Fig. 3).

<sup>4</sup> Height = distance in m above the lowermost exposed portion of layer 1.

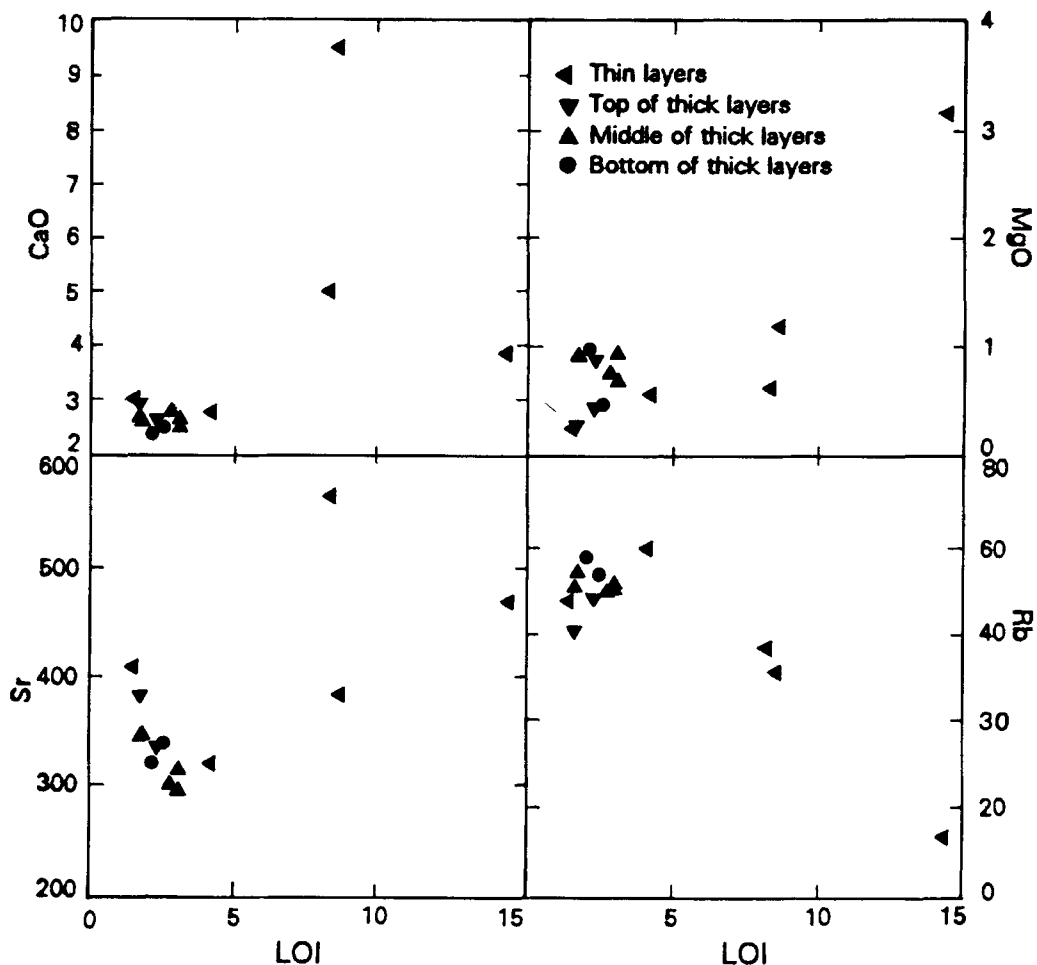


FIG. 5. Plot of selected alkali and alkaline earth metals against loss on ignition. Major element oxides in wt.% volatile free and trace elements (Sr and Rb) in ppm.

There are no clear correlations between the composition of a particular rock type (e.g. middle of thick layer samples) and height (layer).

**Discussion**

*Alteration*

The elevated CaO and MgO, high LOI and presence of microcrystalline carbonate in three thin layer samples (LC2A1, LC8A1 and LC8A2) strongly suggest that calcite and/or dolomite were added to the samples with concomitant losses and gains of various other elements. The relatively unaltered thin layer samples (LC3A and LC2A2) have major element compositions which are very

similar to thick layer samples (Table 1). This similarity makes it difficult to explain the friable nature and preferential weathering of the thin layers entirely in terms of primary rock characteristics. Carbonate addition, alteration and preferential weathering, have combined to accentuate small primary chemical variations between thick and thin layers in the unit. Why the alteration seems to have mainly affected the thin layers is examined in subsequent paragraphs.

*Statistical identification of rock groups*

Relatively altered thin layer samples are excluded from an analysis of primary igneous processes.

The variation diagrams (Fig. 6) indicate that thin layer samples can be distinguished from thick layer samples, but it is not clear whether samples from the top, middle and bottom of thick layers form distinct groups. To determine if they can be distinguished the data were examined using multidimensional scaling (MDS) and SYSTAT statistical software (Wilkinson *et al.*, 1992, pp. 109–31). MDS summarizes multidimensional geochemical similarities and differences between samples in a two-dimensional space placing similar samples close together and chemically dissimilar samples apart. Distances between samples were calculated from Pearson correlation coefficients derived from standardized (all elements were put on the same scale using z-scoring) data. The results suggest that bottom, middle and top thick layer samples are distinct (Fig. 7). Further, judging from dimension 1, middle thick layer samples may have less in common with the thin layer samples than the top and bottom thick layer samples.

Information on the elements distinguishing these four groups of samples could yield valuable information on geological processes that formed the layering. Univariate F-tests indicate that Fe, Mn and Ni, K, Li and Cs, most of the *REE* and Y as well as Zr, Hf, U and Tl are all highly correlated ( $P \leq 0.05$ ) with the groups.

#### Crystal fractionation model

Analysis of the above information and the variation diagrams suggest that the thin layers could represent crystal differentiates derived from the underlying thick layers. For example the decrease in  $\text{Fe}_2\text{O}_3$ , MnO and Ni between the middle thick layer samples and the thin layer samples could reflect biotite removal. The similarity between the major element geochemistry of both thin and thick layer samples makes it difficult to test this hypothesis using mass-balance calculations but it implies small amounts (~10%) of fractionation. Another approach is to use trace elements and the Rayleigh fractionation equation (e.g. Gast, 1968) rearranged to solve for  $f$  (fraction of magma remaining):

$$\ln f = (\ln(C_1/C_0))/(D - 1)$$

where:  $C_1$  = average concentration of each trace element in the relatively unaltered thin layer samples;  $C_0$  = average concentration of each trace element in the underlying middle thick layer samples ( $n = 2$ );  $D$  = the bulk distribution

coefficients for each trace element calculated using phase proportions from thick layer petrography and partitioning coefficients given in Table 2.

If the proposed crystal fractionation model is valid all trace elements should return the same  $f$  value. Modelling parameters and results appear in Table 2. The modelling assumes that the thick layer samples represent liquids. In the strictest sense this is probably not true, but all of these rocks are very fine-grained implying that they approach liquid compositions. It is possible to mathematically mix the thin layer composition back into the thick layer to approximate a pre-differentiation and extraction composition for the thick layers but this has no significant effect on the modelling results. Relatively 'immobile' elements such as the *REE*, Y, and high-field-strength elements (Zr, Hf, Nb, Ta, U, Th), as well as Zn and siderophile elements (Sc, Ni) return a mean  $f$  value of 0.88 ( $n = 24$ ) with a standard deviation of 0.06. Given analytical errors and uncertainties associated with partitioning coefficients and mineral proportions this represents good agreement. A small amount of fractionation is consistent with the similarity, based on major element geochemistry, of thin and thick layer samples.

There are problems with a few elements. The model predicts that Cr concentrations should have decreased. This suggests that the proportion of biotite involved was lower than that used in the model, or that Cr precision (as a percentage) suffers as concentrations approach the limits of detection. Rb yielded a typical  $f$  value (0.88) but Li and Cs behaved antithetically to Rb and K, indicating that alkali metal concentrations may not be reliable even in the least altered samples. Finally Sr and Ba show increased concentrations between the thick layer samples and thin layer samples. The model predicts that Sr should have decreased due to the influence of plagioclase (bulk  $D > 1$  yields  $f = 1.6$  which is impossible unless the thin layers are cumulates). Similarly, Ba yielded a small  $f$  (0.61), reflecting a large bulk  $D$  (0.52) and produced by biotite removal. If the increases in Ba and Sr between average middle thick layer and thin layer samples are due to primary processes then they could reflect selective transport of alkaline earth metals by magma-dissolved volatile complexes. A similar process has been suggested for alkali metal anomalies associated with differentiated layers in basaltic lava flows (Greenough and Dostal, 1992a). An

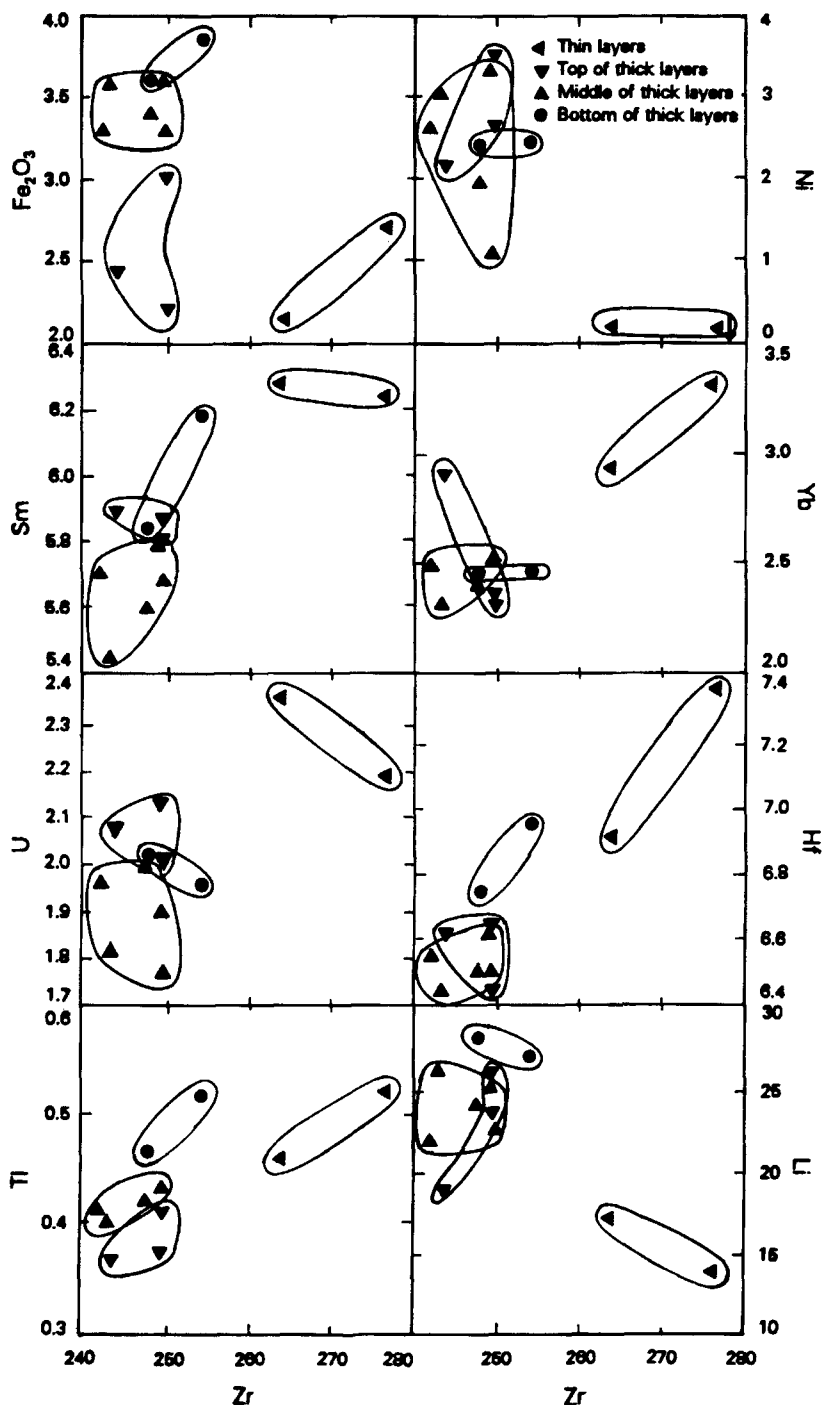


FIG. 6. Variation plot of selected elements against Zr. Only the two relatively unaltered thin layer samples are plotted.  $\text{Fe}_2\text{O}_3$  is in wt.% volatile free with all other elements in ppm. Fields identify samples from the same group.



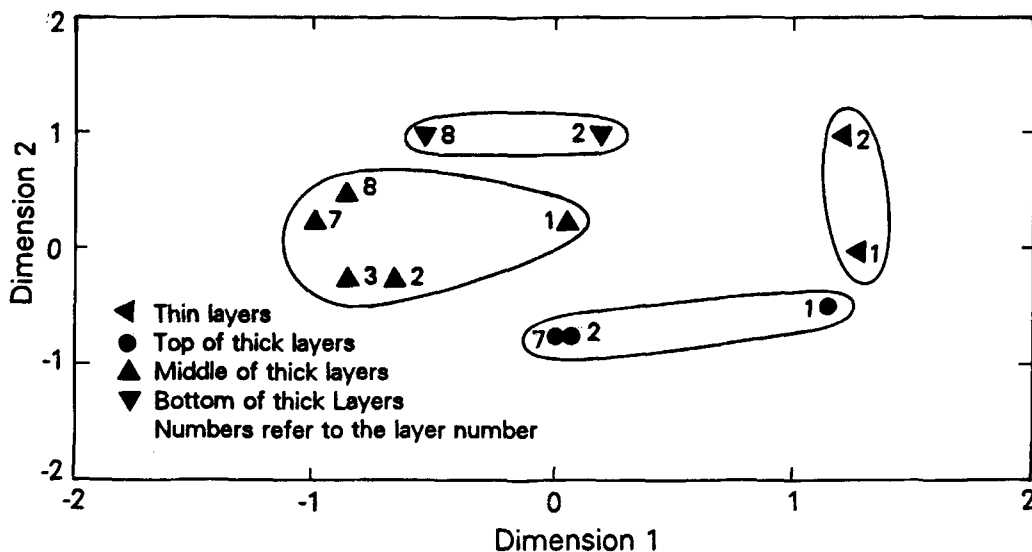


FIG. 7. Multidimensional scaling diagram showing the four sample groups. Fields drawn around samples have no statistical significance but illustrate the tendency for samples from the same group to occur together. See text for discussion.

alternative explanation is that the alkaline earth metal concentrations in even the least-altered thin layer samples, were, like the alkali metals, modified by secondary processes. The above anomalies aside, the semi-quantitative modelling largely supports the crystal fractionation model.

#### Formation of horizontal segregation veins

Crystal fractionation alone does not account for the regular spacing of the thin layers. Possibly they represent the residual liquid marking the top of regularly spaced, thin (~4.5 m) convection cells. Double-diffusive convection cells caused by opposing chemical and thermal gradients within magma chambers have been proposed to explain m-scale layering in some mafic intrusions (e.g. McBirney and Noyes, 1979; McBirney, 1985). At least in the simple case (one phase precipitating and no mixing of convection cell contents with time) models predict that the most mafic compositions should occur near the base of layers and decline smoothly above until rocks from the next cell are encountered (Kruger and Smart, 1987). Some elements in Layer Cake Mountain rocks show no such tendency (e.g. Ni, Sm, Fig. 6). Furthermore, sharp contacts marked by pronounced chemical changes across the top

and bottom boundaries of the thin layers argue against this hypothesis.

The sharp breaks defining the thin layers indicate that they are horizontal segregation veins. Similar-scale to slightly thinner layering (thick layers ~1.3 m separated by segregation veins ~0.3 m thick) occurs in basaltic lava flows (Wright and Okamura, 1977; Helz, 1980, 1987; Greenough and Dostal, 1992a). The horizontal segregation veins form when crystal mush at the lower limit of the downward-crystallizing upper crust tears away from the crust due to thermal contraction (Wright and Okamura, 1977; Marsh, 1990). Gas effervescence filter pressing (Propach, 1976; Anderson *et al.*, 1984) or the 'vacuum' created in the opening crack draws interstitial liquid in (Marsh, 1990; Greenough and Dostal, 1992a). Lack of evidence for gas bubbles in either the thick or thin layers of Layer Cake Mountain argues that the liquid was more likely sucked into the opening crack. Vertical 'fingers' of quenched dacite intruding the base of the thin layers may represent the last drops of liquid to enter the segregation vein. Multidimensional scaling (Fig. 7) indicates that small amounts of the segregated liquid infiltrated the base of the overlying thick layer, and were left behind at the top of the underlying thick layer accounting

TABLE 2. Modelling data and results

	Partitioning coefficients <sup>1</sup>			$f^2$
	Plag.	Bio.	Mag.	
Li	0.1	1.6	0.05	1.82
Rb	0.1	3.0	0.05	0.88
Cs	0.1	2.0	0.05	4.93
Sr	1.8	0.08	0.01	1.64
Ba	0.4	1.1	0.1	0.61
La	0.32	0.035	0.5	0.93
Ce	0.24	0.037	0.6	0.95
Pr	0.21	0.04	0.7	0.93
Nd	0.19	0.044	0.8	0.94
Sm	0.13	0.058	0.9	0.89
Eu	0.3	0.14	0.6	0.90
Gd	0.09	0.082	0.8	0.94
Tb	0.088	0.09	0.8	0.89
Dy	0.086	0.097	0.7	0.89
Ho	0.085	0.13	0.7	0.83
Er	0.084	0.162	0.6	0.85
Tm	0.08	0.17	0.5	0.84
Yb	0.077	0.179	0.4	0.78
Lu	0.062	0.19	0.35	0.77
Y	0.085	0.13	0.7	0.81
Zr	0.015	0.07	1	0.90
Hf	0.015	0.07	1	0.91
Nb	0.02	0.3	1	0.92
Ta	0.02	0.3	1	0.75
U	0.01	0.1	0.25	0.81
Th	0.01	0.1	0.25	0.92
Zn	0.05	10	20	0.90
Sc	0.01	16	5	0.97
Cr	0.01	5	2	4.66
Ni <sup>5</sup>	0.01	40	40	0.82
Pro. <sup>3</sup>	75	20	5	
Ref. <sup>4</sup>	a-j	a,b,f h,j-l	b-e,h k,l	

<sup>1</sup> Partitioning coefficients used are typical values for intermediate to felsic magmas with an emphasis on dacites.

<sup>2</sup>  $f$  = fraction of magma remaining. Values greater than 1 indicate that elements behaved in the opposite manner as predicted by the model. See text for discussion.

<sup>3</sup> Mineral proportions used for bulk distribution coefficients.

<sup>4</sup> References for partitioning coefficients: a) Schnetzler and Philpotts (1970); b) Cameron and Cameron (1986); c) Lemarchand *et al.* (1987); d) Hendersen (1984); e) Gill, p. 200-201 (1981); f) Moller (1988); g) Barbey *et al.* (1989); h) Worner *et al.*, (1983); i) Fujimaki *et al.* (1984); j) Philpotts and Schnetzler (1970); k) Mahood and Hildreth (1983); l) Giannetti and Luhr (1983).

<sup>5</sup> Modelling assumed a near-background value for Ni in the average vesicular sample, 0.3 ppm.

for small shifts of these samples toward the thin layer samples on the MDS plot (Fig. 7). It is not clear what processes account for the apparently small differences between the top and bottom contact samples.

The layering in Layer Cake Mountain is very different from the zonation inferred for silicic magma chambers (e.g. Hildreth, 1979; 1981; Mahood, 1981). The large chemical variations in the latter occur over vertical distances of hundreds to thousands of metres. Secondly, the chemical zonation appears related to volatile movement of complexed elements through thermally zoned magma chambers. Geochemical trends ascribable to these types of processes were not observed in the Layer Cake samples, but then again the sampled section was only ~40 m thick.

### Summary and conclusions

To the authors' knowledge this is the first reported example of layering formed by *in situ* processes in a felsic volcanic unit. Thin layers separating thick layers represent segregation veins formed when the lower crystal mush thermally contracted and fractured. Interstitial liquid was siphoned from the mush as the horizontal crack opened up. The trace element composition of the thin layers can be largely accounted for by crystal fractionation involving only 10 to 15% removal of plagioclase, biotite and Fe-Ti oxides. The small amount of fractionation accounts for the observation that thin layers are very similar to thick layers in terms of their major element composition.

Thin and thick layers are so similar that the layering may have been difficult to identify were it not for overprinting secondary processes. Apparently the thin layers were fractured during cooling to produce zones of weakness for later metasomatic and diagenetic fluids to follow. Fracturing of 'pegmatitic' segregation veins is well documented in the North Mountain Basalt (Greenough and Dostal, 1992b). Zoning in mafic pegmatite minerals is truncated (minerals are broken) at a 'rhyolite' band representing residual liquid that left the segregation vein and moved into the fracture (a second-stage segregation vein).

As a result of the inferred late-stage fracturing process the thin layers have acted as aquifers for solutions that altered primary minerals and locally precipitated carbonates. The altered and carbonated rock weathers more easily, leaving the faulted rock face deeply incised at each thin layer.

We expect that layering is common in felsic composition lava flows, just as it is common in basaltic lava flows, but it will be even less commonly reported due to the difficulty of identification. Apparently the serendipitous superposition of secondary processes on what began as small primary chemical variations in the dacite has resulted in the unique, beautiful and instructive land form known as Layer Cake Mountain.

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