

The Roza Member, Columbia River Basalt Group: A gigantic pahoehoe lava flow field formed by endogenous processes?

T. Thordarson

CSIRO Magmatic Ore Deposits Group, Division of Exploration and Mining, Floreat, Western Australia

S. Self

Department of Geology and Geophysics, School of Ocean and Earth Science and Technology
University of Hawaii, Honolulu

Abstract. We present studies on the physical volcanology of the ~15 Ma Roza Member of the Wanapum Formation in the Columbia River Basalt Group. The Roza Member represents a compound pahoehoe flood basalt lava flow field, with an area of ~40,300 km² and a volume of ~1300 km³. It consists of 4 major lava flows each composed of numerous, decimeter to kilometer long pahoehoe lobes. Roza lavas feature a wide range of pahoehoe surface structures, such as lava rise plateaus, tumuli, and surface breakouts, and we illustrate that the lava morphology is inconsistent with previous proposals of rapid emplacement for these lavas. An integral component of the Roza flow field is the sheet lobe with internal structures identical to those of inflated pahoehoe sheet lobes from Hawaii and Iceland, both at the same scale and at much larger scales. We identify a three-part division of the sheet lobes into basal crust, lava core, and lava crust, which are interpreted as the equivalent to the bottom crust, the liquid lava core, and the surface crust of an active inflating pahoehoe lobe. The upper lava crust grows continuously during lava emplacement and its growth rate can be approximated by conductive cooling. This relationship is used to calculate the emplacement time for individual Roza sheet lobes and to derive a first-order estimate on the duration of the Roza eruption. The results indicate that the emplacement of individual Roza lobes lasted for months to years and that the lava flow field was constructed over a period of at least 14 years. We propose that the Roza flows achieved great areal dimensions and thicknesses by inflation and endogenous growth. As the lava flowed from vent to flow front it traveled under an insulating crust which maintained cooling rates of <0.1°C/km and allowed for efficient transport of lava over distances up to 300 km.

1. Introduction

The prominent feature of Columbia River Basalt Group (CRBG) lava flows is their size, with volumes that are up to 2 orders of magnitude greater than the largest lavas produced by historic and Holocene basalt eruptions, and lengths and thicknesses up to 1 order of magnitude bigger [e.g., *Tolan et al.*, 1989; *Thordarson and Self*, 1996b]. Flood lava emplacement is of interest because of the need to estimate magma discharge and eruption duration for such events. These parameters are important for assessment of eruption dynamics and atmospheric mass loading of volcanic gases. The current debate on flood lava emplacement is strongly polarized and evolves around whether (1) these lavas were formed as turbulent or laminar sheets emplaced in matter of days to weeks or (2) they were emplaced gradually over a longer period (i.e., years to decades) by endogenous processes, involving insulating lava transport and growth by inflation.

Shaw and Swanson [1970] evaluated the mode of lava emplacement for the Roza and other CRBG flows. They pro-

posed rapid turbulent emplacement and extremely high eruption rates. Their treatment is based on the assumption that lavas of the CRBG flowed and were emplaced as 10- to 100-m-thick coherent sheets of lava. They also inferred that the lavas were superheated low-viscosity flows, because the flow lobes and units are typically bounded by a glassy (quenched) selvage regardless of the distance from source. Their proposal was generally adopted without modification [e.g., *Swanson et al.*, 1975; *Hooper*, 1982], although later studies have used other constraints to argue for rapid emplacement of CRBG lavas [e.g., *Reidel and Fecht*, 1987]. Glassy lobe margins indeed indicate minimum cooling of the lava during transport but are not unequivocal evidence for rapid lava emplacement. Thermally efficient lava transport can also be attained by insulating mode of emplacement [e.g., *Flynn and Mouginitis-Mark*, 1992; *Realmuto et al.*, 1992; *Ho and Cashman*, 1997; *Keszthelyi and Self*, this issue], as illustrated by the inflated pahoehoe lavas of the 1983 to present Pu'u'O'o-Kupaianaha eruption at Kilauea volcano in Hawaii [*Mattox et al.*, 1993; *Hon et al.*, 1994]. This style of lava emplacement has been demonstrated for Holocene and Quaternary pahoehoe lava flows world wide by showing that structures such as tumuli, lava rise plateaus, pits, and sutures invariably indicate endogenous growth and lava inflation [e.g., *Walker*, 1991; *Keszthelyi and Pieri*, 1993; *Chitwood*, 1994; *Rossi*, 1996] (see review by *Self et al.* [1998]).

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Theoretically, both emplacement styles are plausible, and the applicability of either model can only be tested by detailed volcanological and petrological studies [Keszthelyi and Self, this issue]. Like most other basaltic lava successions, the CRBG lava flows are characterized by a range of morphologies and structures. Many flows are bounded by pahoehoe surfaces while others are capped by rubbly flow tops but pahoehoe basal surfaces. Internal structures such as jointing style, vesicularity, and crystallinity also vary from one flow to another [e.g., Waters, 1961; Mackin, 1961; Swanson, 1967; Schmincke, 1967]. Long and Wood [1986] identified three end-member flow types (labeled I, II, and III) within the CRBG on the basis of internal structures and textures. Type I flows are typically thin (10-30 m) pahoehoe flows, and the Roza lavas described in this paper generally fall under this type. Type II and III flows are thick (30-80 m) flows, often capped by a thin rubbly flow top and feature well-developed tiers of colonnade and water-cooled entablature.

In Holocene basalt lava flow fields, pahoehoe lava morphology typically indicates slow endogenous emplacement, whereas aa lava morphology reflects rapid emplacement of channelized flows [e.g., Einarsson, 1949; Lipman and Banks, 1987; Rowland and Walker, 1990; Walker, 1991; Keszthelyi and Pieri, 1993; Hon et al., 1994; Pinkerton and Wilson, 1994; Kilburn, 1996]. However, the application of these concepts to the emplacement of flood basalt lava flows is subject to controversy [Thordarson, 1995; Self et al., 1996a,b]. For example, does the pahoehoe morphology always represent a particular emplacement style, regardless of volume and extent? In this study we address this question by presenting new field data on the lava morphology and structures of the Roza Member of the CRBG and by reevaluating previously published data. We illustrate that the Roza consists of numerous inflated pahoehoe lobes and, after presenting field and other evidence, suggest that it represents a giant compound pahoehoe lava flow field produced by a single eruption lasting for more than a decade. The significance of our observations for the mode of lava emplacement and for estimating the duration of the Roza eruption is also discussed.

2. The Roza Member

2.1. Stratigraphic Position

The ~15 Ma Roza Member of the Wanapum Formation (Figure 1) is one of the most widespread lava flow fields of the Columbia River Basalt Group (CRBG) in the Pacific Northwest, covering ~40,300 km² and with an estimated volume of ~1300 km³ [Tolan et al., 1989]. It is defined on the basis of its stratigraphic associations, magnetic polarity, and distinct petrographic and compositional characteristics [Mackin, 1961; Bingham and Grolier, 1966; Wright et al., 1973; Swanson et al., 1979; Martin, 1989, 1991]. The base of the Roza Member is normally sharp and is commonly separated from the underlying flows of the Frenchman Springs Member (FSM) by a 2 to 20-cm-thick silty soil. Over most of the Columbia River Plateau, the overlying lavas of the Priest Rapid Member (PRM) rest directly on the Roza lavas, where the original lava surface commonly shows evidence of being modified by erosion and weathering prior to burial by PRM flows. When the original flow tops are preserved at the upper contact, they feature pahoehoe surfaces [Mackin, 1961]. The upper contact is usually without sedimentary interbeds, with the exception of exposures in south-central Washington,

where volcanoclastic sediments of the Ellensburg Formation partly cover the Roza lavas. Sediment, soils, or evidence of erosion have not been found between the individual, compound lava flows that make up the Roza Member [see also Swanson et al., 1975].

2.2. Roza Vent System and Lava Flows

Outcrops of feeder dikes and near-vent deposits delineate a ~150-km-long and ~5-km-wide linear trend (Figure 1) identified as the Roza vent system [Bingham and Grolier, 1966; Swanson et al., 1975; Martin, 1991]. Individual Roza feeders are 1-7 m wide, simple and composite dikes, with strike directions between 330° and 6° and dips of 82°-90°. Outcrops of scoria fall and welded spatter deposits and fountain-fed (clastogenic) lava flows are scattered along the trend of the Roza dikes, often sandwiched between lava flows [Swanson et al., 1975], suggesting widespread fallout of pyroclastic material caused by episodes of explosive activity and lava fountaining [Self et al., 1997, Figure 11]. Such evidence of explosive episodes during the Roza event is further corroborated by efficient vent degassing of the Roza magma, with ~70% of the dissolved volatile mass released at the vents [Thordarson and Self, 1996a]. Previous studies also noted that at any one locality the Roza Member consisted of one to four readily identifiable flow units and suggested that the member was composed of several regionally extensive and rapidly emplaced lava flows [e.g., Bingham and Grolier, 1966; Martin, 1989].

The Roza lavas are evolved tholeiites, containing 5-18 modal percent phenocrysts of plagioclase (5-12%), clinopyroxene (2-4%), and olivine (1-3%) and rare (<1%) magnetite phenocrysts [Waters, 1961; Thordarson, 1995]. The chemical composition of the Roza Member is remarkably homogeneous (Figure 2), with a variability of major and trace element concentrations in the range of 1-15%, with the exception of Cr (~55% variance; 21-55 ppm). Martin [1989, 1991] identified six regionally extensive chemical subtypes (I-IV) on the basis of subtle changes in lava composition (Figure 2). The established stratigraphy suggests a progressive younging from subtype I to IV. Small changes in the abundance of compatible (e.g., Cr) and incompatible (e.g., Zr, Zn) elements indicate that the magma became slightly less evolved over time.

The Roza lavas are comagmatic and most of the minor compositional changes can be accounted for by crystal fractionation of up to ~9% plagioclase, clinopyroxene, olivine, and magnetite [Martin, 1991]. Martin proposed that each chemical subtype corresponds to one flow (cooling) unit and that each is a continuous sheet of lava formed in a series of six eruptions at intervals of 50-200 years. This interpretation, however, is open to reinterpretation because (1) the chemical subtypes define a continuous trend over a very small compositional range and a considerable overlap exists between subtypes (Figure 2), (2) at any one locality each subtype may correspond to either a single lava lobe (or flow unit) or a package of several lobes (Figure 1b), (3) outlines of each chemical subtype (see Martin [1989], Figure 7) are inferred from outcrop distribution of each subtype and do not correspond to the physically identifiable lava flow margins in the field, and (4) as mentioned above, there is no evidence of significant time breaks within the Roza Member. Thordarson [1995] identified the Roza lavas as consisting of inflated pahoehoe lava flows and offered an alternative interpretation, that it is a giant compound lava flow field formed by a single eruption.

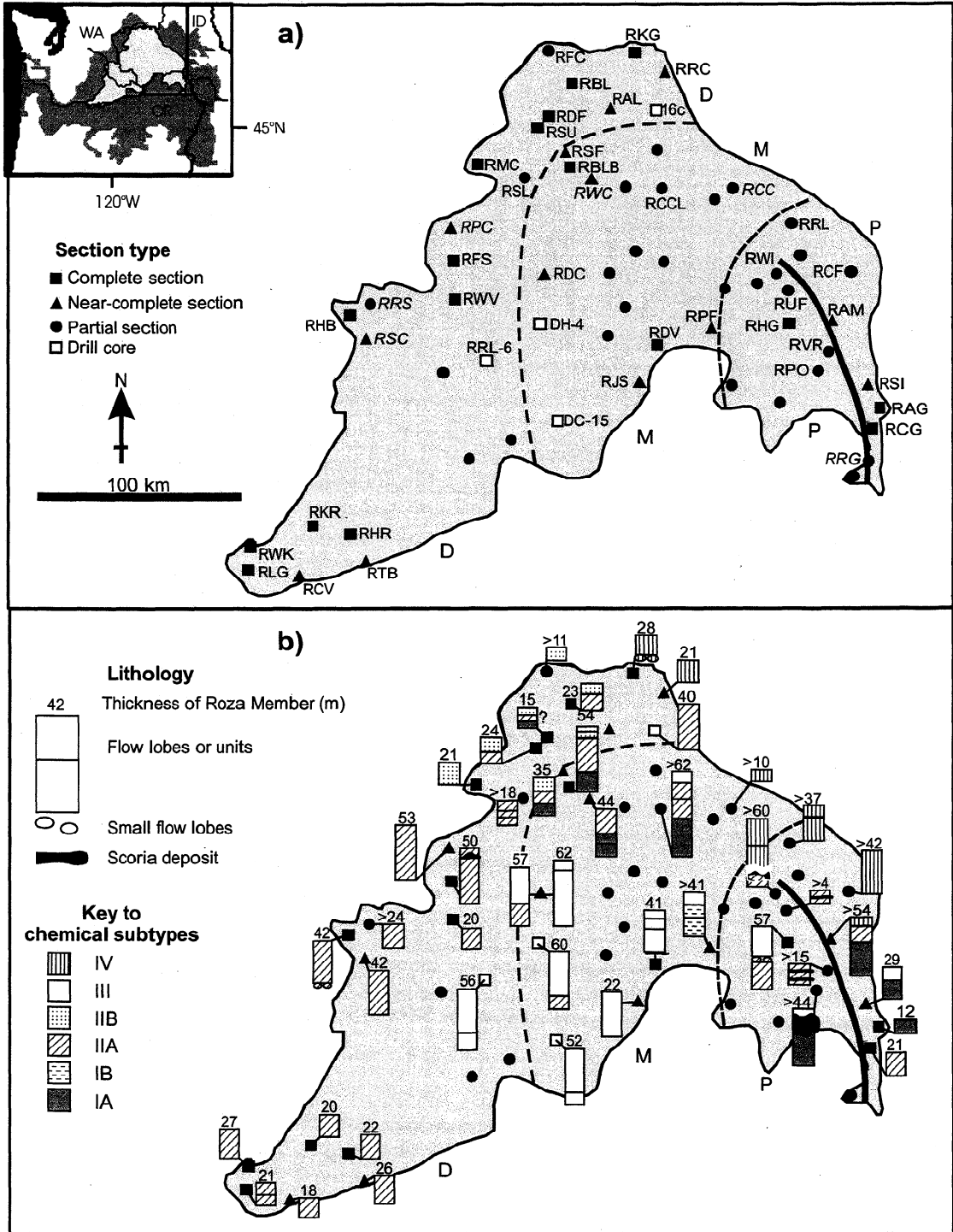


Figure 1. (a) Map outlining the known distribution of the Roza Member. Heavy solid line delineates the Roza vent system [Swanson *et al.*, 1975]. Also shown are localities of stratigraphic sections within the Roza flow field measured in this study and by Martin [1991]. Letter designation are codes for the localities listed in Table 2. Localities indicated by italic font are not listed in Table 2 and are as follows: RCC, Crab Creek; RPC, Potholes Coulee; RRG, Rattle Snake Grade; RRS, Roza Station; RSC, Selah Creek; RWC, Wilson Creek. RRG is the location of the composite dike described in section 4.1. (b) Columns showing the stratigraphic division of the chemical subtypes in the Roza Member. Dashed lines separate P (proximal), M (medial), and D (distal) regions of the lava flow. Inset shows extent of Columbia River Basalt Group (dark shading) and Roza lava flow field (light shading); WA, Washington; OR, Oregon; and ID, Idaho.

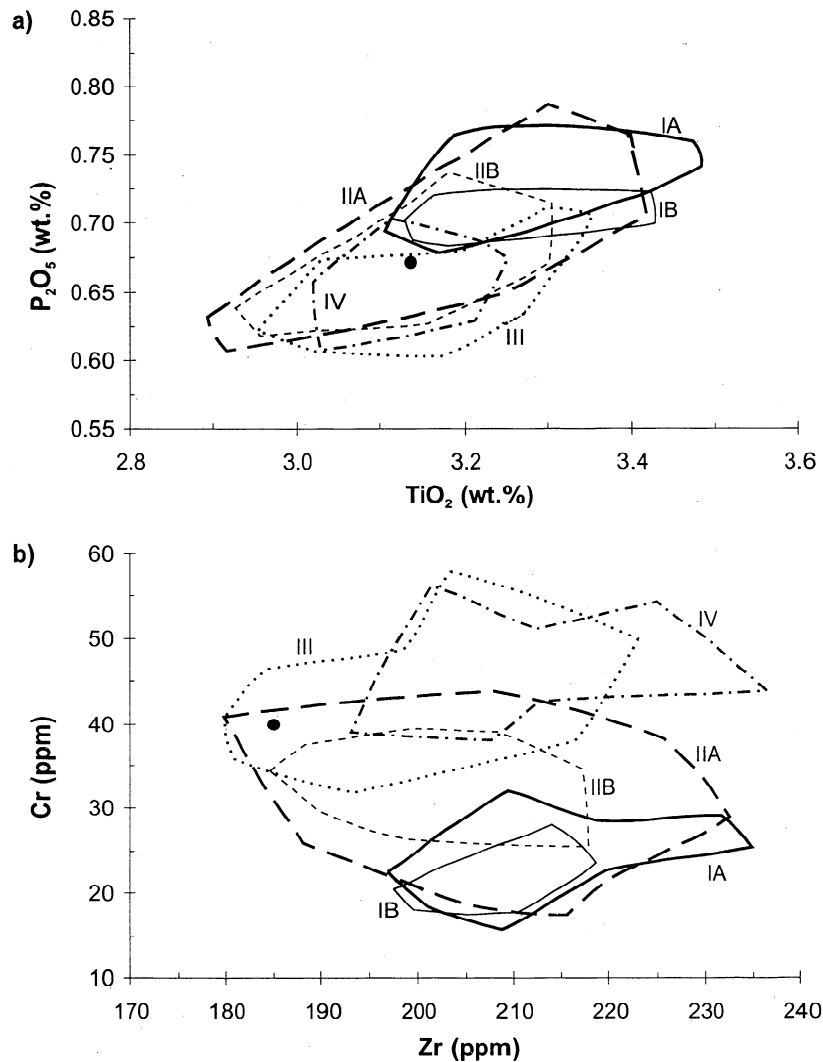


Figure 2. Variation diagrams showing the compositional fields of individual Roza chemical subtypes; (a) P₂O₅ versus TiO₂ and (b) Cr versus Zr. Subtype fields are outlined as follows; IA and IB (heavy and thin solid line), IIA and IIB (heavy and thin long, dashed lines), III (dotted line), and IV (dot dashed line). Solid circle shows the composition of Roza at locality RSL (Soap Lake; discussed in section 4.1). Note that chemical subtypes define a continuous trend over a very narrow compositional range that becomes slightly more mafic with time [Martin, 1991].

3. Field Observations and Methods

3.1. Field Observations

Roza lavas cover a vast area but are largely buried under younger lava flows. Outcrops are restricted to subvertical cliff exposures that are several kilometers apart at best. Outcrops examined are grouped according to distance from source and their position within the Roza Member into four categories: near-vent (<5 km from source), proximal (5-50 km), medial (50-150 km), and distal (>150 km) localities. Outcrop quality varies greatly and they are here ranked accordingly: as good, moderate, and poor in terms of the exposure, and as complete, near-complete, and partial sections in reference to the completeness of the outcrop (see Table 1). These distinctions are useful because quenched lobe margins, packages of small lobes between large lobes, and changes in internal structures are difficult to identify in outcrops of moderate to poor quality. High-quality outcrops are not uniformly distributed across the extent of the Roza Member. Most of the good to moderate quality, complete and near-complete sections are located

within 25 km of the mapped outer margins of the Roza Member. Outcrops in the interior are mostly partial sections of poor quality (Figure 1a). However, in other pahoehoe fields in Iceland and Hawaii, flow morphology and structures are very similar wherever the field is examined, near the margins or in the interior [e.g., Mattox *et al.*, 1993; Rossi, 1996].

3.2. Methods

We focused our attention on good quality outcrops identified as complete and near-complete sections by Martin [1991]. A few good quality partial sections are also included. Detailed graphic logs were made at each locality, recording the texture, vesiculation, and jointing style on a decimeter to meter scale. Surface structures and the nature of contacts were also examined and sketched. In this manner, we methodically obtained information on the morphology and internal structure of the flows from 16 localities (Figure 1 and Table 2). These data are complemented by information obtained from graphic logs at 25 localities measured by Martin [1991], in-

Table 1. Terminology and Definitions

Term	Definition
	<i>Outcrops</i>
Quality	indicates how much of the outcrop is obscured by talus or vegetation: good (g), <10%; moderate (m), 10-30% and poor (p), >30%
Completeness	complete sections (C), outcrops where the Roza lava succession, including upper and lower contacts of the member, is fully exposed; near-complete sections (NC), outcrops where the contacts of the member are not exposed, but can be positioned within 2 m; partial sections (P), outcrops with partial exposure of the lava succession where the member contacts cannot be positioned
	<i>Contacts</i>
Distinct	contact featuring clearly separated glassy pahoehoe surfaces
Annealed, fused,	contact between lobes marked by a centimeter thick glassy band formed by fusion of the original lobe surfaces
Discontinuous	contact between lobes which dissipate or disappear when followed in outcrop
	<i>Lava</i>
Lava flow field	a complex body of lava identified on the basis of field relations and chemistry as the product of one eruption; may consist of several lava flows
Lava flow	a regional subunit formed during a continuous effusive event; may in some cases correspond to a single eruption; may consist of many flow lobes
Flow lobe	a single unit of lava surrounded by a glassy (chilled) crust, varying in long dimension from decimeters to several kilometers and up to 60 m thick
Sheet lobe	a lobe with a flat or gently undulating flow surface produced by one continuous outpouring and injection of lava; much wider and longer than thick, and can be tens to thousands of meters in long dimensions
Breakout	a small lobe originating as an outbreak of lava from the molten interior of a previously formed lobe; lobe margin and surface breakouts, lobes formed as breakouts through the front (or sides) and the upper surface of the feeding lobe, respectively
	<i>Vesiculation Pattern</i>
Vesicles	molds of gas-filled voids frozen in the lava, referred to as microscopic (<2 mm in diameter) and macroscopic (>2mm)
Diktytaxitic texture	microscopic (≤ 2.0 mm), irregular intercrystalline voids, outlined by crystal faces of adjacent groundmass minerals [Fuller, 1931]
Pipe vesicles and Vesicle cylinders	roughly cylindrical pipes of near-vertical orientation that are hollow in the former case and filled with vesicular segregated material in the latter
Horizontal vesicle sheets	sheets of vesicular segregated material, centimeters to tens of centimeters thick, that are continuous (>50 m long) and discontinuous (1-10 m long) on an outcrop scale; previously identified as segregation veins [Kuno, 1965] or vesicle sheets [Goff, 1996]
Segregation vesicles	irregular, spherical to elongate vesicles lined with segregation material [Smith, 1967]; often V- or U-shaped in cross section and are several mm to 10 cm long and most commonly occur within or just above the basal vesicular zone
Megavesicles	dome-shaped voids with flat floors and arched to dome-shaped roofs, with dimensions ranging from several to tens of centimeters; floored by moderately vesicular to nonvesicular glassy segregated material and occurring in close association with horizontal vesicle sheets
Large vesicles	elongate or spherical vesicles, 1-10 cm in diameter; may contain segregated material
Gas-blisters	large tens to hundreds of centimeter long cusped-shaped voids with a bubble-textured floor and roof that typically occurring near the top of pahoehoe lobes; commonly connect to laterally extensive parting surfaces [Walker, 1989]
Vesicular zone	decimeter to meter thick horizons with >10 vol% of macroscopic vesicles
	<i>Jointing Style</i>
Columnar zone	lower one-half to two-thirds of flow distinguished by elongate to blocky, four to five sided columns and 1-3 m joint spacing; generally corresponding to the colonnade
Crustal zone	upper one-half to one-thirds of flow, distinguished by uneven and irregular, tapering columns and 0.5-1.5 m joint spacing, with joint density (number per unit length) of 2-3 times that of the columnar zone
Platy zone	characterized by densely spaced, horizontal joints, defining centimeter thick and decimeter long disk-shaped plates
Flow-top joints	short regular prismatic joints that occur in top 1-2 m of flow
	<i>Petrographic Texture</i>
Crystallinity	relative abundance of crystals versus glassy mesostasis is indicated by holocrystalline (crystallinity of 90-100%), hypocrystalline (50-90%), hypohyaline (10-50%), and holohyaline (0-10%) [Mackenzie et al., 1982]

cluding thickness values of the Roza Member, number and thickness of individual flow lobes or units, and nature of the upper lava crust. We used indicated changes in vesicularity and jointing style on Martin's logs to estimate the thickness of the upper crust. This method was tested by comparing sections measured separately in both studies. Differences range from 2 to 15%, verifying the compatibility of the two data sets (e.g., compare sections RSF and RBL in Table 2).

The thickness data used in this study include only measurements from complete sections and near-complete sections where the base and top of the member and/or internal flow lobes/units can be located with reasonable accuracy (± 2 m). Joint patterns were evaluated by measuring joint spacing and describing the column geometry. Where possible, joint propagation directions were estimated by using the method of DeGraff et al. [1989], but the indicators are poorly developed in

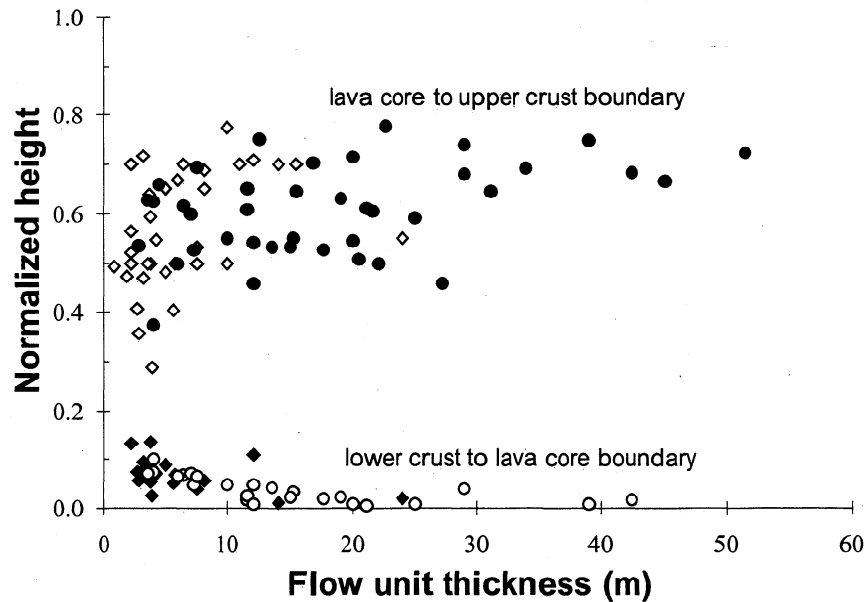


Figure 3. Normalized height h/l (h , height in lobe; l , total lobe thickness) of the two common levels where the main structural properties change within Roza and other CRBG sheet lobes plotted against lobe thickness. Lower crust to lava core boundary is shown by open circles (average of 0.04 ± 0.02) and solid circles show the lava core to upper crust boundary (average of 0.60 ± 0.09). Measurements from Icelandic and Hawaiian lavas listed in Table 4 are also shown as filled and open diamonds.

the Roza lavas and often do not yield consistent results. Vesicularity and crystallinity were estimated visually in the field with the aid of graphic charts and a hand lens. Degree of crystallinity was reassessed in the laboratory by microscopic examination of hand-specimens and thin sections, and crystallinity of glassy selvages was determined by point counting in thin sections [Thordarson and Self, 1996a]. Our reporting on mesostasis abundance does not differentiate between clear sideromelane glass and tachylite (i.e., microcrystalline mesostasis).

3.3. Terminology

Before describing the Roza lavas it is appropriate to define our terminology, because it includes new terms that enable effective communication of the concepts relevant to emplacement of the Roza lava flows. We use the terms lava flow field, flow, and lobe in concordance with Self *et al.* [1997], and these terms are defined in Table 1. Note that both lava flows and lobes can correspond to the field-mapping term flow unit, which does not discriminate between the two former identities.

Systematic documentation of internal features in pahoehoe sheet lobes is an important component of this study, and we identify three key groups of internal features: 1) vesiculation pattern, 2) jointing style, and 3) petrographic texture. The structures of each group are defined in Table 1. Vesiculation pattern is defined by distribution, mode, shape, and size of vesicles and other degassing features. Petrographic texture refers to crystallinity and crystal size, properties that are controlled by a number of parameters, such as volatile content, cooling rate, and crystal nucleation rate. Jointing style refers to the arrangement and morphology of cooling joints and columns. Jointing style in Roza pahoehoe sheet lobes is similar to that of type I flows of Long and Wood [1986] and Roza lobes lack well-developed entablature. However, the jointing styles in the lower and upper parts of these lavas show significant differences, and here we use the terms columnar zone

and crustal zone to indicate these styles (Table 1). We avoid the use of colonnade and entablature because of their previous association with models of water cooling for the entablature [Long and Wood, 1986].

Pahoehoe sheet lobes are characterized by a distinct distribution of internal structures and a three-part division is identified from their vertical arrangement [Aubele *et al.*, 1988; Thordarson, 1995; Self *et al.*, 1997; Cashman and Kauahikaua, 1997]: 1) the vesicular hypocrySTALLINE base or the basal crust; 2) the columnar-jointed holocrystalline lower part or the lava core; and 3) the vesicular hypocrySTALLINE upper part or the lava crust. The boundaries of these divisions are identified by marked changes in vesiculation pattern, jointing style, and petrographic texture, which are typically found to converge at two common levels within sheet lobes (Figure 3). The lower level marks the transition from basal crust to lava core; the upper level defines the boundary between the lava core and the upper lava crust [Thordarson, 1995; Self *et al.*, 1997; Cashman and Kauahikaua, 1997]. Normally, changes in vesiculation structures are the best indicators of the transition from crust to core, followed by a change in jointing style. Changes in petrographic texture are the least distinct of the three.

4. Lava Morphology and Structures

4.1. Internal Characteristics and Lava Morphology

The stratigraphic thickness of the Roza Member across the Columbia River Plateau ranges from 11.5 to 67.0 m (average of ~36 m), and the frequency distribution of thickness values has three distinct peaks at 20-25 m, 40-45 m, and 55-60 m (Figure 4a). Distribution of thick and thin successions is erratic and no correlation is observed between stratigraphic thickness of the Roza Member and distance from source or proximity to flow margins (Figures 1 and 4b). The thickness-frequency distribution primarily reflects the number of vertically stacked flow lobes or units at each locality and to a

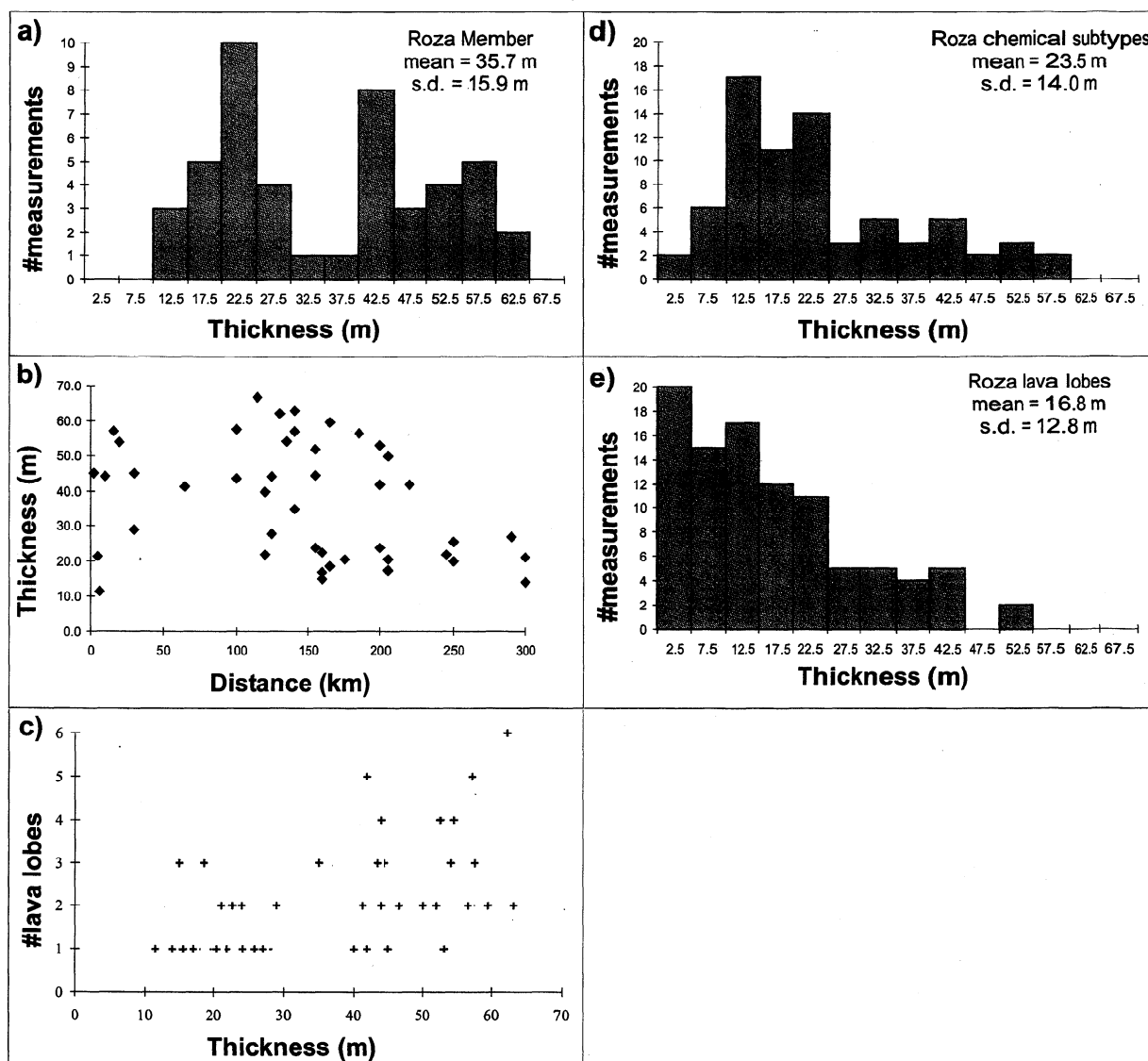


Figure 4. (a) Frequency distribution of total measured stratigraphic thicknesses of the Roza Member at individual localities. Also shown is the mean stratigraphic thickness and standard deviation (1σ). (b) Stratigraphic thickness of the Roza Member at individual localities plotted against distance from source. Note the erratic distribution of thin and thick successions. (c) Stratigraphic thickness of the Roza Member plotted against number of lava lobes identified at each locality. (d) and (e) Frequency distribution of measured thickness in Roza chemical subtypes and lava lobes, respectively.

lesser extent the difference in thickness of individual lobes between localities (Figure 4c). The thickness of individual Roza chemical subtypes at any one locality ranges from 17.0 to 57.5 m (average of ~23 m, Figure 4d) and the thickness distribution is skewed, peaking at 10–15 m and gradually tapering off toward larger values.

The thickness of individual Roza lava lobes ranges from 0.4 to 52.0 m (average of ~16.7 m). Figure 4e shows that lava lobes <5 m thick have the highest frequency (~20%) and that most of the measurements fall in the thickness interval between 5 and 25 m (~57%). Again, the thickness of individual lobes shows no correlation with distance from source (Table 2).

Characteristics of the Roza lava succession are here illustrated by sequential descriptions of the internal stratigraphy and lava morphology at near-vent to distal localities (Table 2). Simplified stratigraphic columns of relevant sections are

shown on Figure 1b; detailed descriptions of internal flow structures are presented in section 4.2.

4.1.1. Feeder dikes and near-vent associations. Twenty-four dike segments, assumed to be feeders, have been located along the Roza fissure system and most have subtype IA (15) and IIA (6) composition [Martin, 1991]. Subtypes IB and III are represented by one dike each. At locality RRG (Figure 1) a ~5-m-thick composite dike features injections of two magma batches, an initial dike injection of subtype IA that was split by a later injection of subtype IIA magma. The contacts between the two dike compositions show no sign of quenching and the otherwise horizontal joints of the subtype IA dike are curved upward on either side of the subtype IIA dike. This indicates that the subtype IA dike was still hot when the second dike injection occurred.

Roza near-vent successions are exposed at 15 poor quality partial sections [Swanson *et al.*, 1975; Martin, 1991]. Most

Table 2. Stratigraphic, Flow, Lobe, Core, and Upper Crust Thickness of Roza Member

Locality name	Locality Code ^a	Section Class. ^b	Chemical Subtype ^c	Unit Ident ^d	Stratigraphic Thickness, m	Lava Flow Thickness, m	Lava Lobe Thickness, m	Lava Core Thickness, m	Lava Crust Thickness, m	Ratio h/f ^e	Emplacement Time ^f , years
Near-vent localities											
Union Flat Creek Road	RUF	Pg	IIA	RUF1	>4.0	>4.0	>1.5		>1.5		>0.04
				sfd			1.0		-		
			IIA?	RUF2			>1.5	>1.5	-		
Valantine Ridge Road	RVR	Pm	IIA	RVR1	>15.0	>3.0	>3.0	-	>3.0		>0.17
				sfd			0.3		-		
			IIA?	RVR2		>11.0	4.0	2.6	1.4	0.65	0.04
				spl			0.4				
				spl			0.8				
				spl			1.3				
				spl			1.5				
				sfd			0.5				
			IIA	RVR3			>3.0	>3.0			
Winona	RWI	NCg	IIA	RWI1	>60.0	>7.0	>2.5				
			IIA	spl			2.0				
			IIA	spl			2.5				
			IIA?	sfd		6.0	6.0				
			III	wsd		1.5	1.5				
			IV	RWI2		25.0	25.0				
			IV	RWI3		20.0	20.0				
Proximal localities											
Asotin	RAG	Cm	IIA	RAG1	11.5	11.5	11.5	7.5	4.0	0.65	0.30
Horton Grade	RHG	Cp	IIA	RHG1	57.1	25.0	20.0	14.0	6.0	0.70	0.68
			IIA	spl/psb?			2.0				
			IIA	spl/psb?			2.0				
			IIA	spl/psb?			1.0				
			III	RHG2		32.1	32.1	17.1	15.0	0.53	4.23
Pomeroy	RPO	Pg	IA	RPO1	44.0	>20.0	>20.0				
			IA	rcgs			8.0				
			III	RPO2		>5.0	>5.0				
Almota ^e	RAM	NCp	IA	RAM1	>54.0	31.5	31.5				
			IIA	RAM2		14.5	14.5				
			IV	RAM3		>8.0	>8.0				
Campbell Grade ^e	RCG	Cg	IIA	RCG1	21.5	21.5	21.5	13.0	8.5	0.60	1.36
Colfax ^e	RCF	Pg	IV	RCF1	>41.0	>41.0	>41.0	>26.0	15.0		4.23
Rock Lake ^e	RRL	Pg	IV	RRL1	>36.5	>36.5	>22.0	>11.5	10.5		2.07
			IV	RRL2			12.5	7.5	5.0	0.60	0.47
Silcott ^e	RSI	NCm	IA	RSI1	29.0	17.5	17.5	<14	>3.5		>0.23
			IV?	RSI2		11.5	11.5	8.0	3.5	0.70	0.23
Medial localities											
Devils Canyon	RDV	Cg	III	RDV1	41.0	41.0	31.0	21.1	9.9	0.68	1.84
			III	psb			1.5-10.5				
			III	RDV2			7.3	4.7	2.6	0.64	0.13

Table 2. (continued)

Locality name	Locality Code ^a	Section Class. ^b	Chemical Subtype ^c	Unit Ident ^d	Stratigraphic Thickness, m	Lava Flow Thickness, m	Lava Lobe Thickness, m	Lava Core Thickness, m	Lava Crust Thickness, m	Ratio h/l ^e	Emplacement Time ^f , years
Drumheller Channels 1 ^h	RDC	NCg	III	RDC2	63.0	52.0	52.0	37.7	14.3	0.73	3.85
			III?	RDC3		9.0	9.0	5.0	4.0	0.56	0.30
Drumheller Channels 2 ^h	RDC	NCg	IIA	RDC1	57.0	21.0	21.0	12.5	8.5	0.60	1.36
			III	RDC2		36.0	36.0	26.4	9.6	0.73	1.73
Summer Falls	RSF	NCg	IA	RSF1	35.0	12.0	12.0	6.5	5.5	0.54	0.57
			IIA	RSF2		12.0	12.0	6.0	6.0	0.50	0.68
			IIB	RSF3		>11.0	>11.0	7.0	>4.0	-	>0.30
Black Butte ^g	RBLB	Cg	IA	RBLB1	54.3	17.3	17.3	12.3	5.0	0.71	0.47
			IIA	RBLB2		31.0	31.0	20.0	11.0	0.65	2.28
			IIB	psb		7.2	2.8	1.5	1.3	0.54	0.03
			IIB	psb			4.4	2.9	1.5	0.66	0.04
Jones School ^g	RJS	NCm	III	RSJ1	21.8	21.8	21.8				
Lamona ^g	RCCL	Pp	IA	RCCL1	>62	>34.5	>34.5				
			IIA	RCCL2		17.5	17.5				
			IIA	RCCL3		15.0	15.0				
			III	RCCL4		>11.0	>11.0				
Palouse Falls ^g	RPF	NCp	IB	RPF1	41.3	17.5	17.5				
			IB	RPF2		11.5	11.5				
			III	RPF3		>12.0	>12.0				
Summer Falls ^g	RSF	NCg	IA	RSF1	35.0	11.0	11.0	6.5	4.5	0.59	0.38
			IIA	RSF2		12.5	12.5	7.5	5.0	0.60	0.47
			IIB	RSF3		>11.5	>11.5				
Hanford DH4 ^g	DH4	DH	IIA	DH-4-1	59.5	16.0	16.0	9.5	6.5	0.59	0.79
			III	DH-4-2		43.5	43.5	37.5	6.0	0.86	0.68
Hanford DC15 ^g	DC15	DH	III	DC15-1	52.0	52.0	12.5	8.7	3.8	0.70	0.27
				DC15-2			39.5	25.5	14.0	0.65	3.69
Distal localities											
Banks Lake	RBL	Cg	IIA	RBL1	22.5	15.3	15.3	8.4	6.9	0.55	0.90
			IIB	RBL2		7.2	7.2	3.8	3.4	0.53	0.22
Dry Falls	RDF	Cm		RDF1	15.0	15.0	6.5				
				RDF2			5.5				
				RDF3			5.0				
Frenchman Springs Coulee	RFS	Cg	IIA	RFS1	50.0	50.0	42.5	29.0	13.5	0.68	3.43
			IIA	RFS3			7.5				
Horseshoe Bend	RHB	Cg	IIA	spl	42.0	42.0	0.4				
			IIA	spl			0.3				
			IIA	spl			0.8				
			IIA	spl			1.5				
			IIA	RHB1			39.0	23.5	15.5	0.60	4.52
Lyle	RLG	Cg	IIA	RLG1	21.0	21.0	10.0	6.0	4.0	0.60	0.30
			IIA	RLG5			11.0	6.5	4.5	0.59	0.38
Moses Coulee	RMC	Cg	IIB	RMC1	20.5	20.5	20.5	12.3	8.2	0.60	1.26

Table 2. (continued)

Locality name	Locality Code ^a	Section Class. ^b	Chemical Subtype ^c	Unit Ident ^d	Stratigraphic Thickness, m	Lava Flow Thickness, m	Lava Lobe Thickness, m	Lava Core Thickness, m	Lava Crust Thickness, m	Ratio h/l ^e	Emplacement Time ^f , years	
Soap Lake	RSL	Pg	IIA	RSL1	>18.0	>5.0	>5.0	>2.0	3.0		0.17	
				RSL2		>13.0	>10.0	>10.0				
				RSL3			6.5	3.7	2.8	0.57	0.15	
				RSL4			4.5	2.0	2.5	0.44	0.12	
				RSL6				>12.0	9.5	>>2.5		>>0.12
Almira ^g	RAL	NCm	IA	44.5	14.0	14.0						
			IIA		20.5	20.5						
			IIB		10.0	10.0						
Banks Lake ^g	RBL	Cg	IIA	22.5	16.0	16.0	9.0	7.0	0.56	0.92		
			IIB		9.0	9.0	5.0	4.0	0.56	0.30		
Celilo Village ^g	RCV	NCm	IIA	17.5	17.5	17.5	11.5	6.0	0.66	0.68		
Foster Coulee ^g	RFC	Pg	IIB	RFC1	>11.0	>11.0	>11.0	>6.0	5.0	-	0.47	
Harrison Ridge ^g	RHR	Cg	IIA	RHR1	22.0	22.0	22.0	11.0	11.0	0.50	2.28	
Keller Grade ^g	RKG	Cg	IV	pb	28.0	28.0	2.5					
				RKG1			25.5	20.5	5.0	0.80	0.47	
Little Klickitat River ^g	RKR	Cg	IIA	RKR1	20.0	20.0	20.0	12.5	7.5	0.63	1.06	
Redwine Canyon ^g	RRC	NC	IV	RRC1	20.0	20.0	20.0	13.0	7.0	0.65	0.92	
Sun Lake ^g	RSU	Cg	IIA	RSU1	23.9	11.0	11.0	6.5	5.5	0.59	0.57	
			IIB	RSU2		12.9	12.9	5.7	7.2	0.44	0.98	
The Burn ^g	RTB	NCm	IIA	RTB1	25.5	25.5	25.5	17.0	8.5	0.67	1.36	
Wahkiacus ^g	RWK	Cg	IIA	RWK1	27.0	27.0	27.0	15.0	12.0	0.56	2.71	
Wanapum Village ^g	RWV	Cg	IIA	RWV1	20.4	20.4	20.4	10.0	10.4	0.49	2.03	
Hole 16-C ^g	16-C	DH	IIA	16-c-1	40.0	40.0	40.0	26.5	13.5	0.66	3.43	
Hanford RRL-6 ^g	RRL6	DH	III	RRL-6-1	56.5	56.5	16.0	13.5	2.5	0.84	0.12	
				RRL-6-2			40.5	33.9	6.6	0.84	0.82	

^aLocality code of Martin [1991] used where applicable; all localities are shown on Figure 1b.

^bDesignation for outcrop completeness and quality; C, complete section; NC, near-complete section; P, partial section; DH, drill hole; g, good; m, moderate; p, poor.

^cRoza chemical subtypes IA, IB, IIA, IIB, III, and IV as defined by Martin [1989, 1991].

^dDesignation of lobe types: RUF1 etc., pahoehoe sheet and flow lobes; spl, small pahoehoe lobes; pfb, breakout from margin of lobe; psb, pahoehoe surface breakouts; pb, pillow basalt lobes; sfd, scoria fall deposit; wsd, welded spatter deposit; rcgs, rootless cone deposit.

^eh/l, ratio of lava core thickness to total lobe thickness of a lobe, giving the relative height of the core to upper crust boundary.

^fEmplacement time for each lava lobe, calculated using lava crust thickness and empirical equation of Hon et al. [1994]. See discussion in section 5.7

^gData obtained from sections measured by Martin [1991]; rest from this study.

^hSections measured on opposite side of a coulee at Drummheller Channels, ~ 0.7 km apart.

are small (up to 50 m long x 5 m high) outcrops of welded spatter and clastogenic lavas, or scoria beds interstratified with thin pahoehoe lobes. The best exposures are at Winona (locality RWI on Figure 1), where two outcrops form an ~1-km-long ENE to WSW trending section almost perpendicular to the vent system. The lower contact is not exposed at this locality. The lowest part of these sections consists of thin, highly vesicular (spongy), pahoehoe lobes of chemical subtype IIA that are partly interleaved with the overlying scoria deposit (Figure 5; see also Figure 2 of *Thordarson and Self* [1996a]). The scoria deposit occurs as series of 1 to 8-m-thick, interconnected mounds and is poorly consolidated. It is crudely bedded, featuring several 40- to 100-cm near-horizontal layers of nongraded medium lapilli scoria, separated by 2- to 4-cm-thick reversely graded layers of coarse ash to fine lapilli. The deposit contains rare 6- to 20-cm scoria and spatter bombs and clast vesicularity ranges from 40 to 80 vol%. The topmost 0.5-1.0 m of the scoria deposit are incipiently to densely welded and the horizontal bedding is trun-

cated by this horizon. This sequence is partly concealed by a 1.0- to 2.5-m-thick welded spatter deposit of subtype III composition, which grades into 15- to 25-m-thick, microcrystalline and poorly vesicular clastogenic lava of subtype IV composition. The contact between the scoria deposit and the overlying units is typically annealed and marked by a centimeter-thick red-oxidized glassy band. In several places, the upper part of the scoria deposit is dissected by up to 3-m-long and 0.5-m-wide veins of lava that are bounded by quenched centimeter-thick selvages. These veins connect to the base of the overlying clastogenic lava but do not extend through the scoria pile and are surface-fed lava fingers invading cracks in the scoria [Thordarson and Self, 1996a]. The topmost lava unit in the section is 15-20 m thick and consists of several pahoehoe flow lobes. The surface of this unit features tumuli, revealed as up-domed structures with an axial crack bounded by tilted crustal slabs.

4.1.2. Proximal sections. Out of 12 proximal outcrops described by *Martin* [1991], 3 are complete, 2 are near-

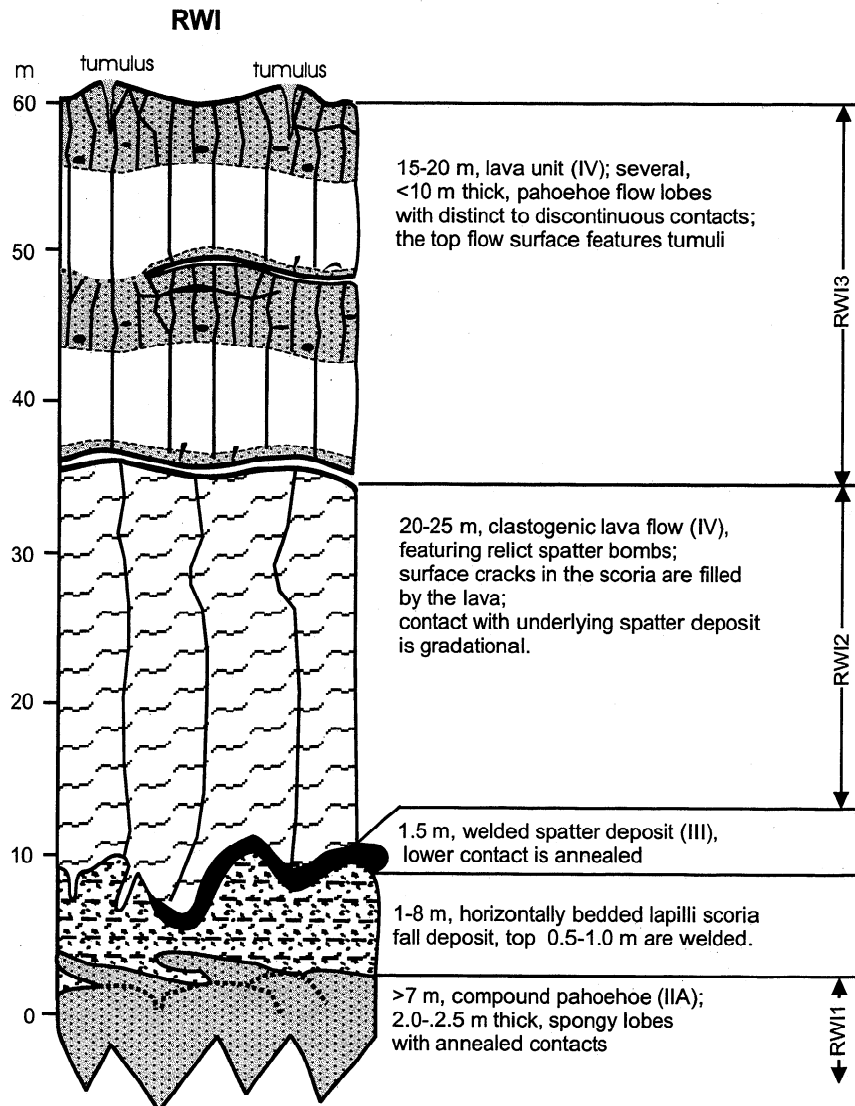


Figure 5. Stratigraphic section of the Roza Member at locality RWI (Figure 1 and Table 2), illustrating the characteristics of the near-vent successions. The succession consists of basal S-type pahoehoe lavas [Walker, 1989] that are intercalated with and overlain by a scoria fall deposit, which again is capped by welded spatter deposit and thicker lava flows (see text for further details). Dot dashed lines indicate discontinuous contacts and Roman numerals indicate chemical subtype of units.

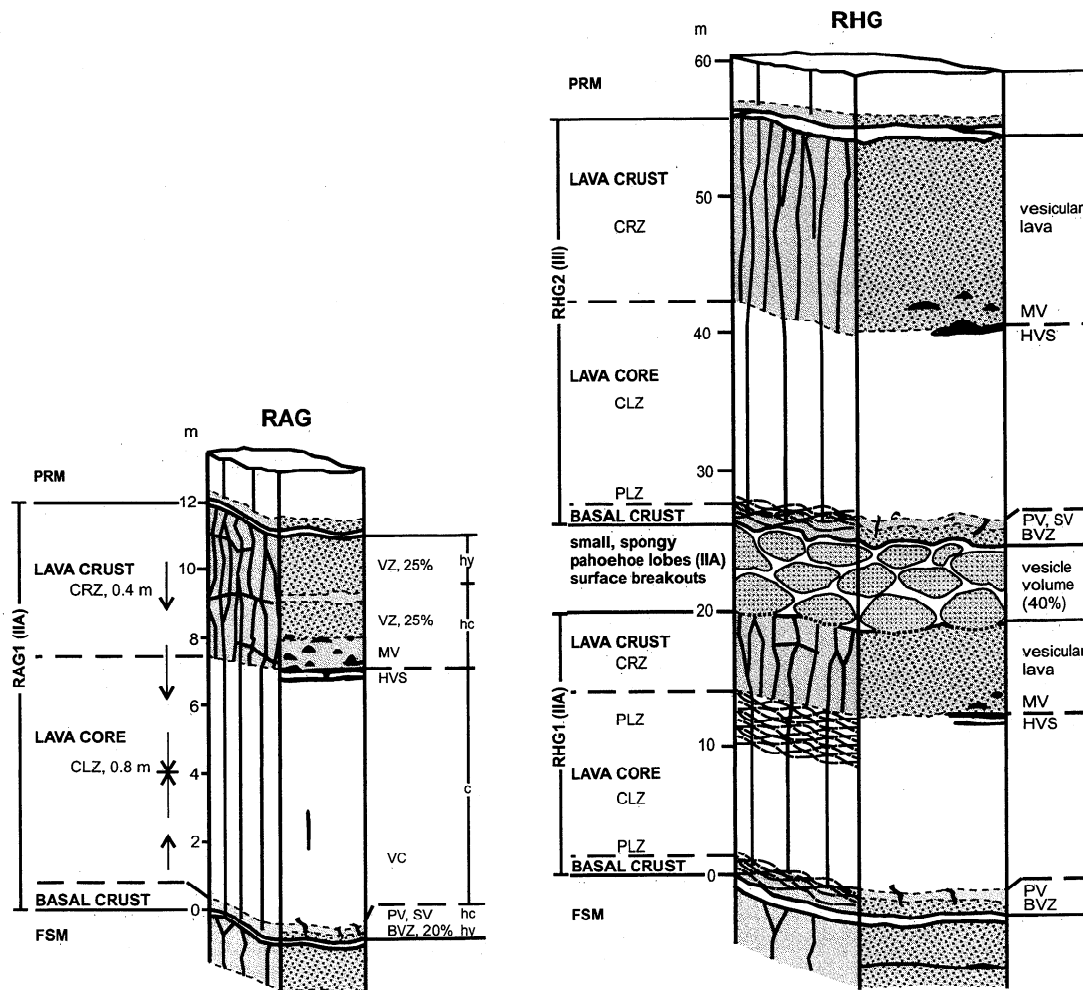


Figure 6. Graphic logs of the Roza Member at proximal localities RAG and RHG (Figure 1 and Table 2), showing stratigraphy and internal structures of the lobes. Right side of the stratigraphic column shows vesiculation features and textural properties, and the left side shows jointing styles. Columns are at different scales and vertical arrows to the left of column in RAG indicate joint propagation directions. Abbreviations are as follows: CRZ, crustal zone (number indicates joint spacing in meters); CLZ, columnar zone; PLZ, platy zone; VZ, horizontal vesicular zone in the lava crust (number indicates volume percent vesicles); BVZ, basal vesicular zone; PV, pipe vesicles and small vesicle cylinders; SV, segregation vesicles; VC, vesicle cylinder; HVS, horizontal vesicle sheet; MV, megavesicle horizon; LV, large vesicles; hy, hypohyaline; hc, hypocrystalline; c, holocrystalline. Dot dashed lines indicate discontinuous contacts and Roman numerals on far left indicate chemical subtype of units. FSM and PRM indicate lava flows of the Frenchman Springs Member and the Priest Rapids Member, respectively.

complete sections, and 7 are partial sections. Outcrops to the east and west of the vent system contain lavas of chemical subtypes IA, IB, IIA and III. Lavas of subtype IV occur at outcrops to the north, and at locality RRL the subtype IV lava consists of two lobes (Figure 1). We measured proximal sections at localities RAG, RHG, and RPO in detail (Table 2).

At locality RAG the Roza Member consists of a single, 10- to 14-m-thick sheet lobe of subtype IA, bounded by gently undulating pahoehoe surfaces, thinning and thickening in phase with highs and lows in the underlying surface (Figure 6). Two pahoehoe flow lobes are exposed at locality RHG, 25 and 32 m thick, respectively. Compositionally, the lower lobe belongs to chemical subtype IIA, and the upper belongs to subtype III. The poor quality of the outcrop made it difficult to obtain measurements of internal structures. However, the available exposure shows that the lobes feature the typical three-part division of pahoehoe sheet lobes, i.e., thin vesicular

basal crust, a nonvesicular lava core, and a vesicular upper crust (Figure 6 and Table 2). These sheet lobes are separated by an ~5-m-thick package of small (<2.0 m) pahoehoe flow lobes that in places have annealed contacts with the lower sheet lobe. The contact with the upper sheet lobe is always sharp. At Pomeroy (locality RPO; Figure 1) a 2- to 10-m-thick rootless cone ramparts occur between two partly exposed lava lobes of chemical subtypes IA and III [Thordarson and Self, 1996a].

4.1.3. Medial sections. Twenty-one sections described by Martin [1991] are considered medial localities and include 4 complete, 5 near-complete, and 12 partial sections (Figure 1). Two of the complete sections are from drill cores of unexposed lava. Lavas of subtypes IA, IIA, and IIB are exposed at medial sections to the north and subtypes IB and III lavas outcrop farther to the south, each consisting of one to three pahoehoe flow lobes at individual localities. Subtype IV is only

exposed at one medial locality to the northeast. We measured detailed sections at localities RDV, RDC, and RSF (Table 2).

At RDV the Roza Member consists of two pahoehoe sheet lobes of subtype III composition (Figures 1 and 7a). The lower lobe (RDV1) is 25-31 m thick and rests directly on an ~0.5-m-thick scoria deposit formed by rootless eruptions (described in section 4.3). The upper lobe (RDV2), >7.3 m thick, is bounded by an eroded upper surface. Lobe RDV1 features a 21-m-thick lava core with uneven, 1.5- to 4.0-m-wide col-

umns, capped by a 1- to 2-m-thick platy zone. The vesicular lava crust is ~10 m thick and features distinct vesicle zones and a horizon of megavesicles and horizontal vesicle sheets at its base. The top of lobe RDV1 is characterized by 80- to 100-m-wide sectors with gently undulating (1-3 m amplitude; 10-30 m wavelength), pahoehoe surfaces which are bounded by steeply dipping (20°-60°) surfaces on either side. The dipping surfaces extend up to 10 m down into the lobe and mark the edges of areas with raised crust. The gap between these sec-

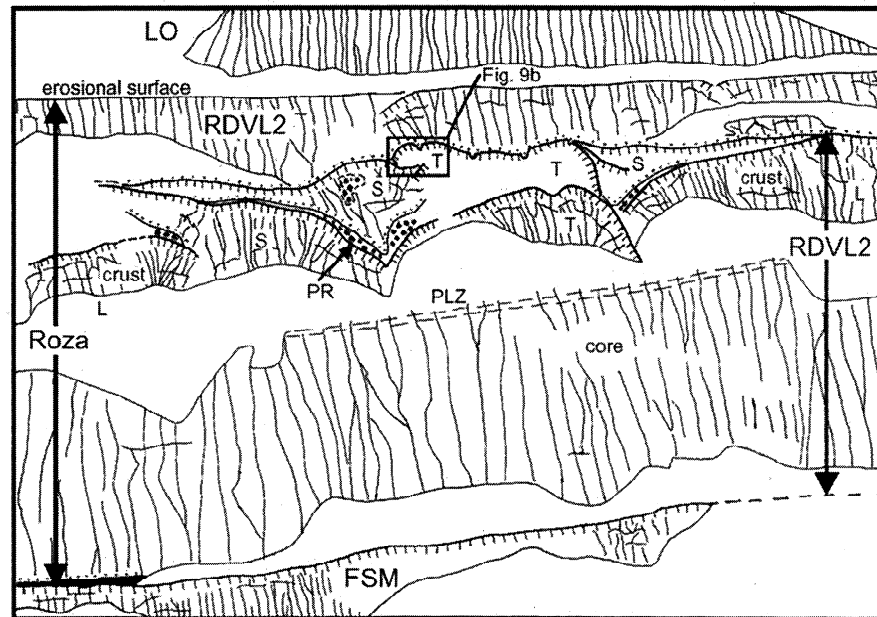
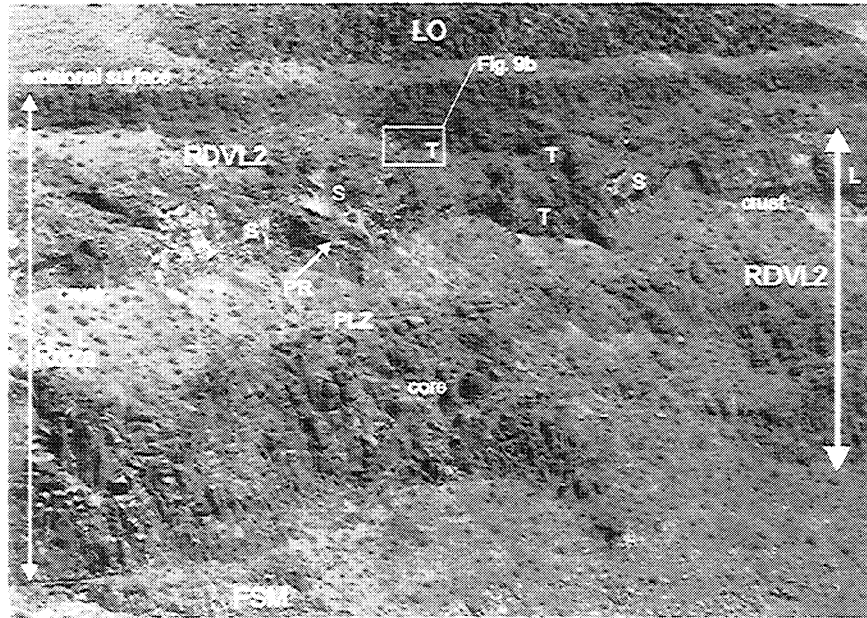


Figure 7a. Two sheet lobes (RDV1 and RDV2) of Roza Member in east wall of Devil's Canyon (locality RDL on Figure 1), the lower lobe is ~31 m thick, and the upper is >7.3 m thick and bounded by an erosional upper surface. The surface of the lower lobe (RDV1) features tumuli (see Figure 7b) and steeply dipping surfaces, marking the edges of lava riser plateaus (L). The gap in between is filled with smaller lobes (surface breakouts; S). Hatchured lines indicate surface, and dotted lines indicate the base of lobes. PR indicates rubble horizons consisting entirely of pahoehoe crustal slabs. Scoria deposit (black) from rootless eruptions is exposed at the base of Roza (bottom left). Below and above are Sentinel Gap flow of Frenchman Springs Member (FSM) and Lolo flow of Priest Rapids Member (LO), respectively.

tors is filled with small (1.5-10.5 m thick), laterally discontinuous pahoehoe lobes. When the steeply dipping surfaces are followed up section, they sometimes wrap around and connect to the basal surface of the smaller discontinuous lobes, showing that they originated as surface breakouts from lobe RDV1. The surface breakouts are sometimes separated from the RDV1-surface by discontinuous rubble horizons, up to 3 m thick and 10 m long. The rubble consists of angular pahoehoe crustal slabs and blocks. The upper lava surface also features 3- to 15-m-high and 5- to 30-m-long tumuli outlined by steeply dipping crustal slabs which have an axial

crack at the crest (Figure 7b). Small bulbous lava squeeze-ups are also found in cracks on the side of these tumuli, whereas the central cracks are invaded by fingers of the overlying lava. The margins of these invasive lava fingers are marked by 1- to 2-cm-thick glassy (quenched) selvages. The upper sheet lobe features a pahoehoe base, but the upper surface is leveled by erosion, and only the lowest 2.5 m of the upper vesicular crust is preserved.

Two sections were measured at locality RDC on either side of an ~700-m-wide WNW to ESE trending scabland channel, cutting through the Priest Rapids and Roza Members, and into

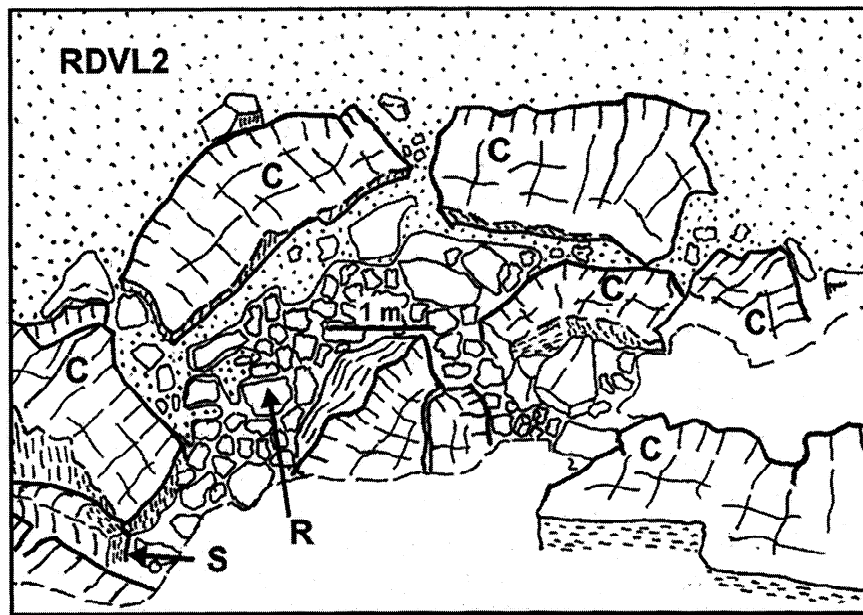
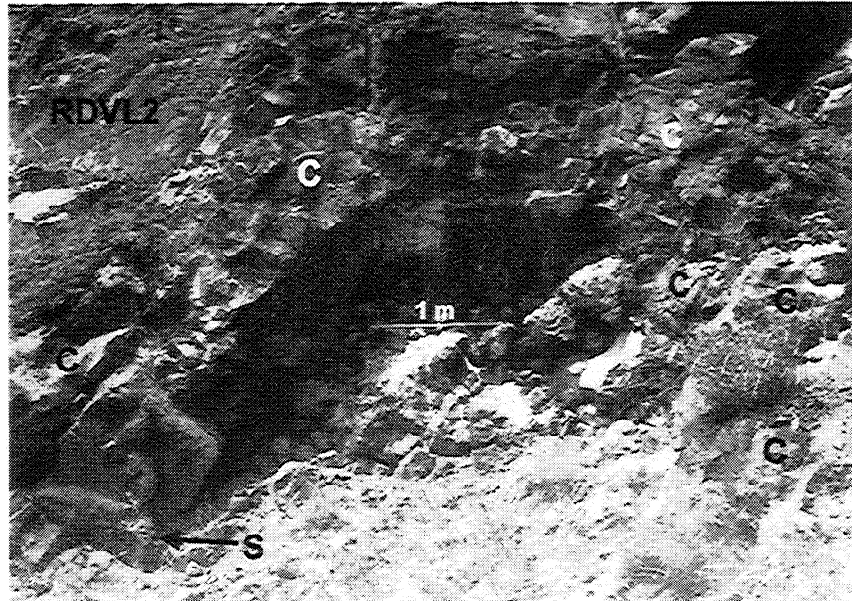


Figure 7b. A close up of a tumulus in upper surface of sheet lobe RDV1 (see inset on Figure 7a), exposed as cupola-shaped structure outlined by the steeply dipping crustal slabs (C). Rubble (R) in the center of tumulus consists of angular pahoehoe crustal blocks, formed by partial collapse of roof when lava was drained from the interior. A lava squeeze-up (S) from the lobe interior is seen in lower left. Also note that lava of overlying sheet lobe (RDV2) invaded cracks in the tumulus.

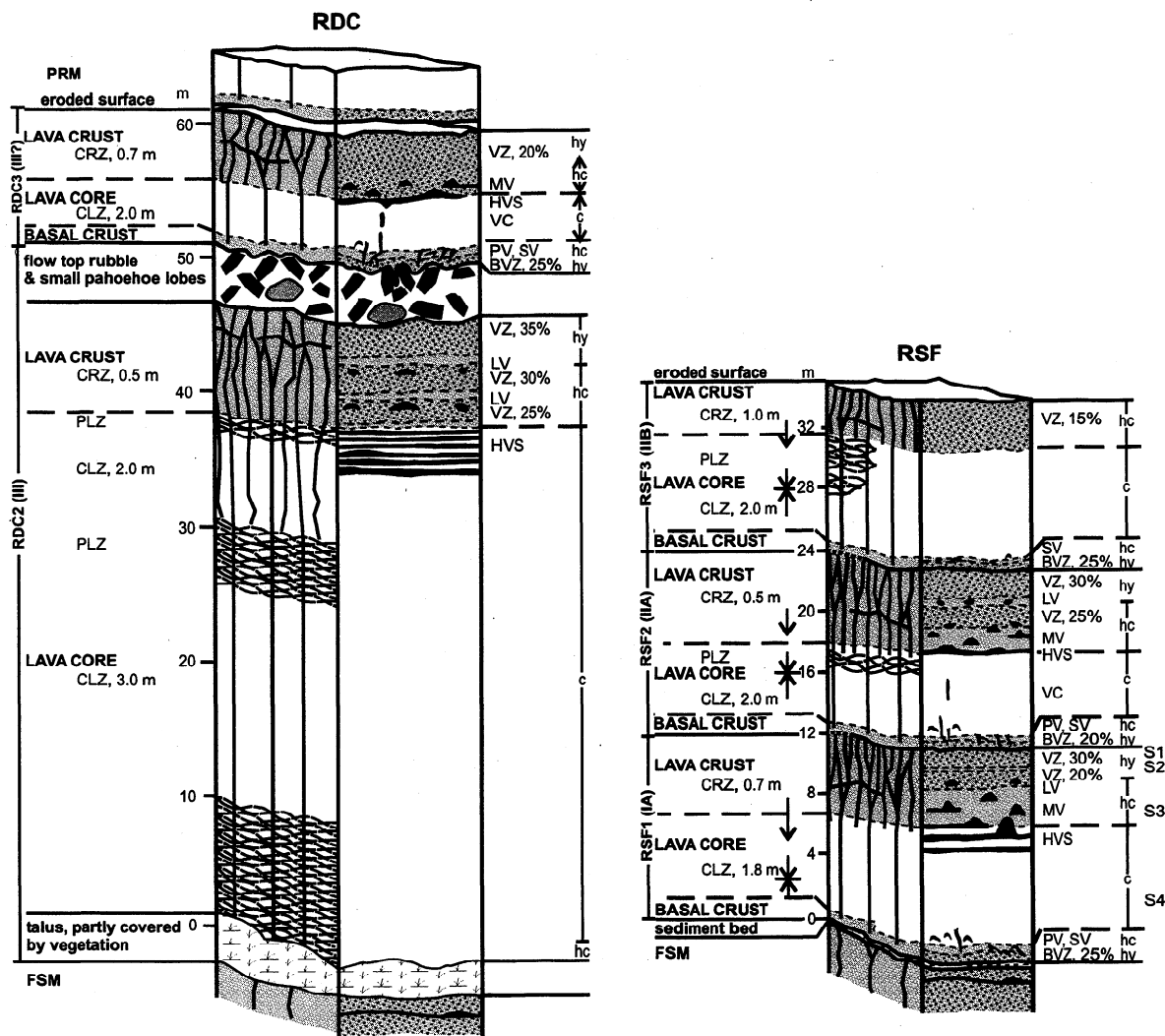


Figure 8. Graphic logs of Roza Member at medial localities RDC and RSF (Figure 1 and Table 2), showing stratigraphy and internal structures of the lobes. Right side of column shows vesiculation features and textural properties; left side shows jointing styles. Columns are at different scales and vertical arrows to the left of column in RSF indicate joint propagation directions. Dot dashed lines indicate discontinuous contacts and Roman numerals on far left indicate chemical subtype of units. FSM and PRM indicate lava flows of the Frenchman Springs Member and the Priest Rapids Member, respectively. See Figure 6 for key to other abbreviations.

the Frenchman Springs Member. In the northern channel wall the Roza Member consists of two flow lobes (labeled RDC2 and RDC3, Figure 8), containing 8-12 vol% plagioclase phenocrysts. The lower lobe (RDC2) is a 52-m-thick sheet that can be followed laterally for ≥ 1 km, thinning to ~ 30 m before disappearing under vegetated talus slopes. It is capped by a 2- to 6-m-thick rubbly flow top consisting of ≤ 1 -m-long slabs of pahoehoe crust and intercalated meter-size pahoehoe lobes. The vesicular upper crust is 9-11 m thick and is underlain by a 4.5-m-thick horizon of megavesicles and a series of continuous horizontal vesicle sheets. The nonvesicular, columnar jointed lava core is ~ 38 m thick and has several distinct platy jointed horizons, two near the top and one at the base (Figure 8). The basal contact is covered by a 3- to 10-m-high talus slope. The upper lobe (RDC3) rests directly on the flow top rubble of RDC2 in the western part of the outcrop. It is ~ 9 m thick and displays the typical three-part division of pahoehoe sheet lobes. The smooth pahoehoe base of lobe RDC3 drapes clasts of the underlying flow top rubble, which is also invaded

by lava fingers up to 10 cm wide. The upper surface of RDC3 has been leveled by erosion and represents an erosional unconformity. In adjacent outcrops to the northwest the overlying Priest Rapids Member lavas rest directly on this erosional surface.

On the south side of the channel, the Roza Member again consists of two flow lobes. The upper lobe is chemical subtype III, containing 6-11 vol% plagioclase phenocrysts. It is correlated with lobe RDC2 in the north channel wall because it has identical internal structures and is capped by a 2- to 4-m-thick slabby pahoehoe flow top. The lower lava lobe (RDC1; Table 2) is chemical subtype IIA, with 3-6 vol% of plagioclase phenocrysts and is missing in the northern wall section. The lower and upper contacts of RDC1 are not exposed in the south wall, but $\sim 75\%$ of the total thickness is exposed in a series of 15- to 30-m-high and 40- to 100-m-long cliff outcrops, extending for ~ 1000 m. In these outcrops the nonvesicular lava core features 0.8- to 1.2-m-wide, well-developed vertical columns and a 0.5- to 2.5-m-thick arched

platy jointed zone at the top (Figure 9). The overlying vesicular crust, however, is characterized by poorly developed, uneven, and tapering columns that are typically 0.4-0.6 m wide. Moreover, approximately half of the crustal joints extend through the platy zone and are joined to a columnar joint in the underlying core. Near the end of individual outcrops, the otherwise vertical crustal joints change orientation to outward fanning joints, denoting gently to steeply dipping (20° - 70°) cooling surfaces. These are normally matched by an opposite fanning joint horizon in the adjacent outcrop. Field relationships indicate that the cooling surfaces come together in the vegetated lows between the outcrops and that they represent dipping flow surfaces that have been removed by erosion.

At locality RSF the Roza Member consists of three vertically stacked flow lobes of chemical subtypes IA, IIA, and IIB (Figures 1 and 8). All are pahoehoe flows and have the char-

acteristic threefold structural division of sheet lobes. In each, the nonvesicular lava core is characterized by fairly regular 1- to 2-m-wide columns and is capped by a thin (0.1-0.5 m), sometimes discontinuous, platy zone. The upper vesicular lava crust features 0.4- to 1.0-m-wide, uneven, and tapering columns, where one out of every two to three joints continues through the platy zone and joins with the columnar joints of the lava core. The vesicular basal crust is typically 0.1-0.35 m thick, with stretched centimeter-size segregation vesicles and rare steeply inclined pipe vesicles. The upper contact of the basal crust is normally sharp and often contorted. V- or U-shaped megavesicles containing segregation material at their roofs occur in the lowest meter of the lava core, which also features remnants of vesicle cylinders. Up to 1-m-high, dome-shaped megavesicles occur in the lowest part of the upper crust and are commonly interconnected by horizontal vesicle sheets (see also section 4.3). Flow boundaries normally are

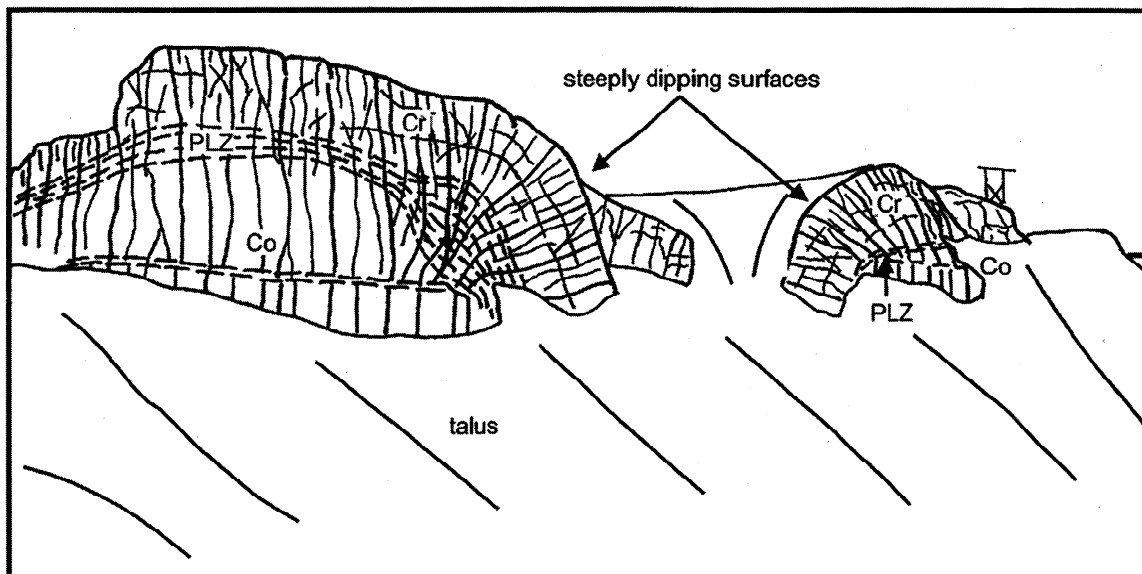
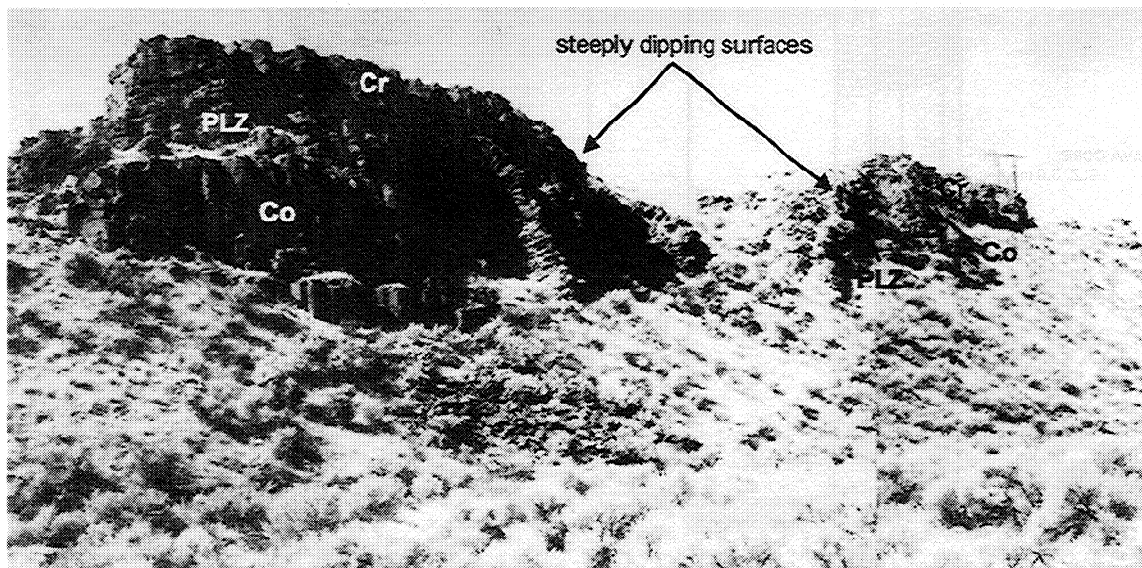


Figure 9. Steeply dipping crustal joint sets (Cr) indicating the location of the boundary (arrows) between two Roza sheet lobes at Drumheller Channels (locality RDC on Figure 1). The orderly columnar jointed set (Co) below is the lava core and is separated from the crust by a platy jointed horizon (PLZ). Height of outcrop is ~15 m.

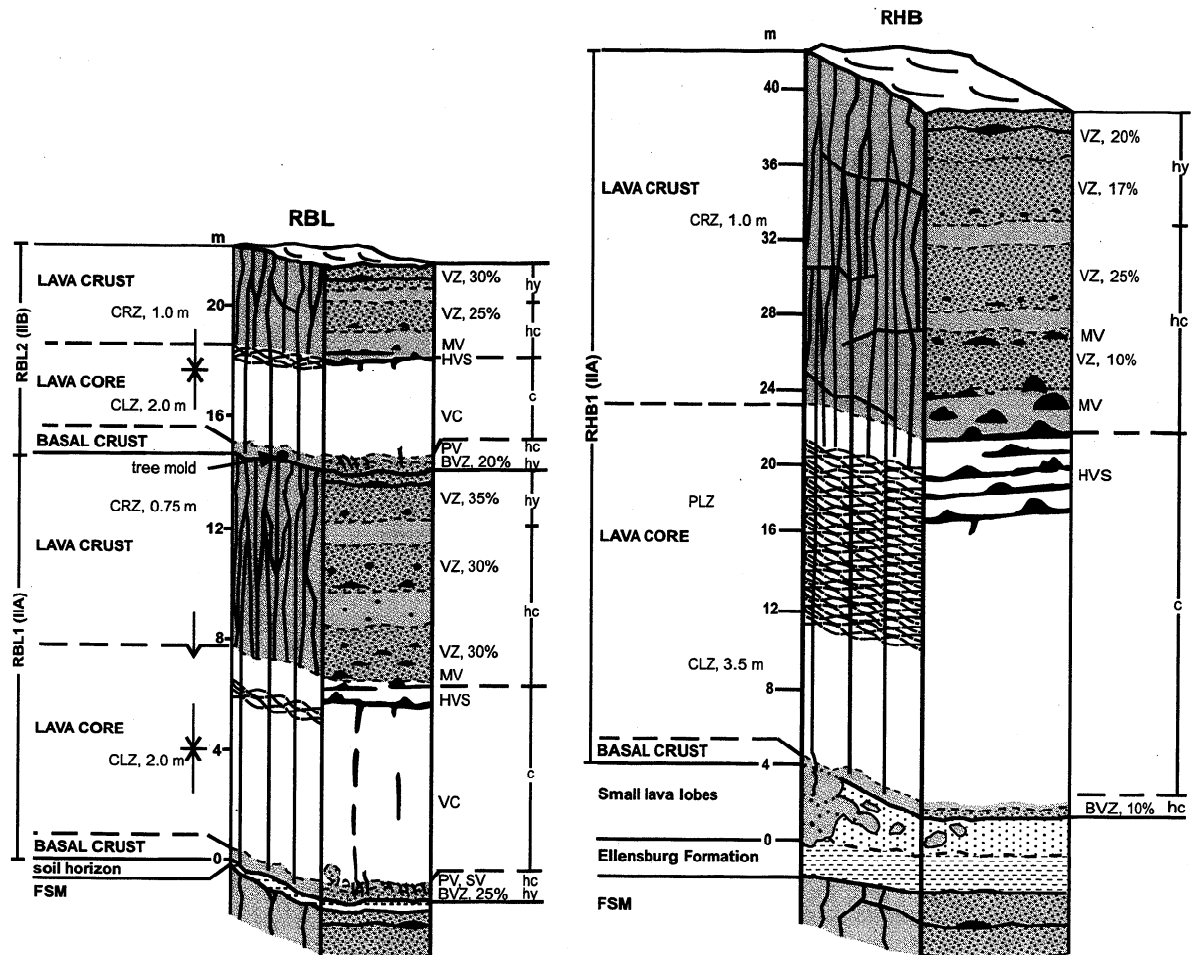


Figure 10. Graphic logs of the Roza Member at distal localities RBL and RHB (Figure 1 and Table 2), showing the lava stratigraphy and internal structures of the lobes. Right side of column shows vesiculation features and textural properties; left side shows jointing styles. Columns are at different scales and vertical arrows to the left of column in RBL indicate joint propagation directions. Dot dashed lines indicate discontinuous contacts and Roman numerals on far left indicate chemical subtype of units. FSM and PRM indicate lava flows of the Frenchman Springs Member and the Priest Rapids Member, respectively. See Figure 6 for key to other abbreviations.

marked by distinct pahoehoe flow surfaces that are sometimes annealed over distances of several meters.

4.1.4. Distal sections. Twenty-five sections from *Martin* [1991] are categorized as distal localities and include 14 complete, 6 near-complete, and 5 partial sections (Figure 1). The complete sections include two drill cores. Subtype IIA lavas are exposed at sections to the west and to the north, where they are overlain by subtype IIB lavas. Subtype IA lava only occurs at one locality, RAL. As for medial localities, subtype III lavas outcrop at localities to the south and subtype IV lavas outcrop farthest to the northeast. At the majority of these localities an individual chemical subtype is represented by a single pahoehoe flow lobe. However, chemical subtype IIA consists of two or more lobes at localities RFS, RSL, RHB, and RLG; subtype IIB is composed of two lobes at locality RAL; and at locality RKG, subtype IV features a package of small pahoehoe lobes below a thick sheet lobe. We measured detailed sections at localities RBL, RDF, RSL, RMC, RFS, RHB, and RLG (Table 2).

At the northernmost locality (RBL) the Roza is composed of two pahoehoe sheet lobes of chemical subtype IIA (RBL1) and IIB (RBL2). Lobe RBL1 rests on a 10- to 30-cm-thick mudstone bed, which covers the pahoehoe surface of the un-

derlying Sand Hollow flow of the Frenchman Springs Member (Figure 10). In addition to the characteristic sheet lobe structures, RBL1 features clusters of pipe vesicles, which are situated where the lava covered shallow lows (≤ 1 m deep) in the underlying surface. These pipe vesicles connect upward to subvertical, 2- to 5-cm-wide vesicle cylinders within the lava core. Well-developed platy zones, along with distinct horizons of continuous horizontal vesicle sheets and megavesicles, occur near the middle of both lobes. The lobe RBL1 is a remarkably flat topped sheet over the distance of the outcrop (~ 100 m), with swales of 0.5- to 1.0-m amplitude and 2- to 5-m wavelength. The original glassy pahoehoe surface along with delicate ropy structures is exceptionally preserved here [Thordarson, 1995]. Horizontal molds after 0.3- to 0.6-m-wide and >3 -m-long tree trunks occur at the contact between lobes RBL1 and RBL2. The molds are shaped into the RBL2 flow base, showing that the original tree trunks were lying on a solidified RBL1 surface when they were engulfed by the upper lobe.

Farther south, at locality RSL (Figure 1), six horizontally and vertically arranged Roza flow lobes are exposed in an ~ 160 -m-long outcrop. The identity of the lavas at this exposure has been questioned by one of the reviewers (B. Martin);

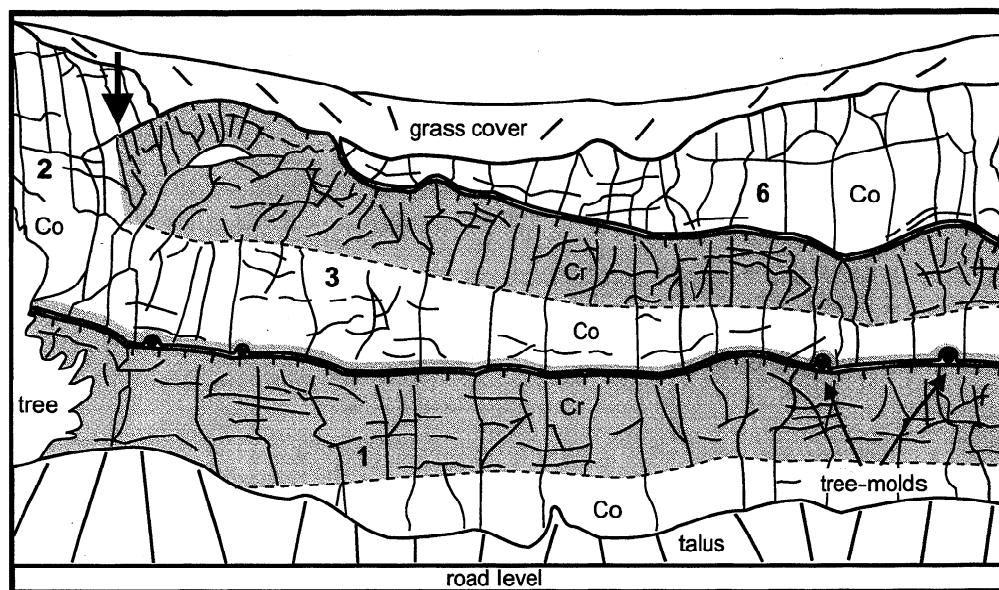


Figure 11. Sketch of compound lava lobes (RSL1, 2, 3, and 6) in Roza at northern end of outcrop at Soap Lake (locality RSL on Figure 1). Hatchured lines indicate lobe surfaces. Dashed line shows boundary between lava core (Co) and upper lava crust (Cr, shaded), and jointing style of each lobe is sketched. Contact between RSL2 and RSL3 is indicated by arrow. Height of outcrop is ~12 m. See text for further details.

however, they are chemically identical to other Roza lavas (Figure 2). They contain ~7 vol% of single, lath-like, 3- to 7-mm plagioclase phenocrysts [Thordarson, 1995], typical of the Roza. The base of the section exposes the top 4-5 m of a pahoehoe sheet lobe (RSL1), extending the entire outcrop (Figure 11). The overlying compound pahoehoe flow package rests directly on the original pahoehoe surface of RSL1. Tree molds identical to that described from locality RBL are found at this contact. At the northern end of the outcrop, the adjoining lobes RSL2 and RSL3 show an interesting relationship. The abutting lobe RSL3 is thickest (~8 m) at the contact with lobe RSL2, thinning rapidly to ~3 m over a distance of 15 m. RSL3 is 45 m long, terminating near the center of the outcrop. The nature of the contact between these lobes (arrow on Figure 11) shows that RSL3 originated as a breakout from the core of RSL2. Lobe RSL6 rests directly on RSL3 but is wedged up against RSL2. In the southern part two additional lobes (RSL 4 and RSL5) occur between lobes RSL1 and RSL6 [Self *et al.*, 1997, Figure 4]. Lobe contacts of RSL1-RSL4 and RSL4-RSL6 are annealed in places. RSL5 is only partially preserved because it has been almost completely assimilated by the later formed lobe (RSL6). Individual columnar joints pass through these two lobes, indicating that they cooled together as a single unit. To the west at locality RMC, situated 5 km from the mapped Roza boundaries, the member is represented by a single pahoehoe sheet lobe of chemical subtype IIB (Figure 1).

In the north wall of Frenchman Springs Coulee (locality RFS on Figure 1) the Roza Member consists of two abutting flow lobes, RFS1 and RFS2 (Figure 12), each 45 to 50 m thick and 500 to 1000 m wide. The flow tops are gently undulating with swales of 1 to 5-m amplitude and 10 to 50-m wavelength. The surfaces feature ropes and areas of uplifted crust with an axial crack, resembling tumuli [Mackin, 1961]. Structurally, these are classical sheet lobes, and the boundary between the lava core and crust is clearly expressed by a distinct change in jointing style. The margins of these lobes come together as curved, steeply dipping surfaces, character-

ized by an outward fanning joint pattern and a lava lobe suture (described in section 4.3). The gap above the suture is filled by a rootless cone rampart and a remnant of a later Roza lobe (RFS3).

Locality RLG consists of two clean road-cuts, ~15 m apart on either side of Highway 14 and is the most distal exposure of the Roza (Figure 1). On the south side of the highway the Roza Member has at least five pahoehoe flow lobes of chemical subtype IIA. These are 8- to 12-m-thick and 20- to 50-m-long, globular lobes bounded by distinct pahoehoe surfaces and feature the characteristic internal structures of sheet lobes (Figure 13a). They have vertical boundaries characterized by curved and contorted glassy (quenched) margins and irregularly fanning joints, but one vertical lobe boundary is marked by a 10-m-wide lava lobe suture identical to that at locality RFS. The lowest Roza lobes rest on a 10- to 30-cm-thick partly carbonized, plant-rich mudstone, which also occurs as irregular mounds of deformed sediments at the vertical lobe boundaries. These mounds formed as the unconsolidated underlying sediment and vegetation was bulldozed and trapped as the lobes came together. Generally, the same relationships are seen in the lower part of the road-cut on the north side of the highway, where vertical boundaries between the lowest lobes are separated by the mudstone mounds. However, moving up section, the lobe contacts become annealed and eventually disappear (Figure 13b).

4.2. Internal Structures of Roza Lavas

As illustrated by Figures 5, 6, 8, and 10, the internal structures of the Roza lavas are fairly uniform regardless of lobe thicknesses or position within the lava flow field. Therefore the following descriptions of internal structures are presented as a synopsis of the observations at all localities, although reference is made to specific outcrops where particular structures are best preserved. A composite log of a Roza sheet lobe is shown on Figure 14.

4.2.1. Vesiculation features. The base of Roza lobes usually features a 5- to 60-cm-thick vesicular zone containing

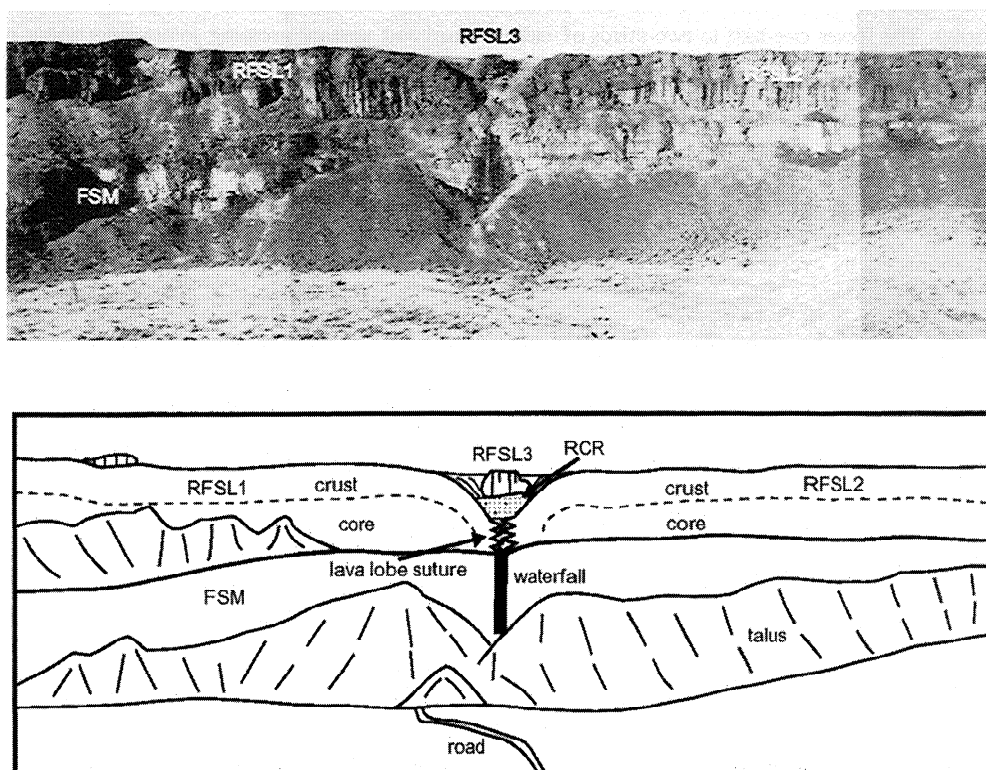


Figure 12. Roza lava flow in North Wall of Frenchman Springs Coulee (RFS on Figure 1) showing two large sheet lobes (RFS1 and RFS2), each 45 to 50 m thick and RFS1 ~1000 m wide. Lobe margins (center on photo) come together as curved, steeply dipping surfaces with consistent rotation of joints. Right above the waterfall the boundary is marked by a lava lobe suture, identical to that shown on Figure 17a and the gap above the suture is filled by a rootless cone rampart (RCR) and a remnant of later Roza lobe (RFS3). Upper part of Roza has been scoured by catastrophic glacial floods that excavated the coulee; the boundary between the lava core and crust is expressed by a sudden change in jointing style (see text). The underlying flows (FSM) are Frenchman Springs Member lavas. Cliff is ~100 m high.

≤35 vol% vesicles (Figure 14). The basal vesicular zone (BVZ) is best developed and preserved in relatively thin flows (<15 m). In thick flows it is normally <0.15 m thick, featuring irregularly shaped vesicles and often masked by a ≤1-m-thick platy zone. The lower half of the BVZ typically contains ≤0.1- to 0.2-cm vesicles. The upper half of the BVZ is characterized by irregular 0.5- to 1.5-cm vesicles that frequently contain segregated material. They often show subhorizontal alignment and are stretched. The upper half of the BVZ also contains clusters of 0.5- to 2.0-cm-wide, inclined pipe vesicles and small vesicle cylinders that either extend into the lava core above or terminate abruptly at the basal crust/lava core boundary.

The lava core of Roza sheet lobes is typically poorly vesicular containing scattered (<0.1 vol%) macroscopic vesicles. The lowest 1-2 m of the lava core often contain irregular, V- to U-shaped, 5- to 15-cm segregation vesicles, in addition to inclined (30°-80°) pipe vesicles and small vesicle cylinders (Figure 14). Vesicle cylinders [Goff, 1996] are not common in Roza sheet lobes, although a few 3- to 10-cm-wide cylinders were found in the lava core of most of the lobes examined. Vesicle cylinders are best preserved in relatively thin sheet lobes at localities RSF, RDF, and RBL and in the lowest 3 m of thick sheet lobes at localities RDV and RFS (Figures 8 and 10). At Banks Lake the basal vesicular zone of lobe RBL1 features tightly spaced, 1.0- to 1.5-cm-wide pipe vesicles extending ~0.25 m up into the lava core. These merge with 2- to 5-cm-wide vesicle cylinders that extend to ~5 m above the

flow base. The BVZ also features plume-shaped structures of vesicular material, extending up to 0.8 m into the lava core.

Continuous horizontal vesicle sheets are found in all Roza sheet lobes and are confined to a well-defined horizon about one-half to two-thirds up in the flow. In relatively thin lobes (≤12 m) the horizontal vesicle sheet zone is ≤1.0 m thick, but in an ~50-m-thick flow unit at Drumheller Channels, it is 4.5 m thick (Figures 6, 8, and 10). In the lower part of the zone the vesicle sheets are typically 5 to 15 cm thick, decreasing in thickness upward to about 1-4 cm. Dome-shaped and flat-based megavesicles up to 1 m high and vesicular pods often extend from the upper surface of the vesicle sheets into the lava above. At the same level the vesicularity of the sheet lobes increases sharply. Above this level, the upper vesicular crust features 1- to 3-m-thick vesicular zones alternating with thinner vesicle-poor zones. The vesicular zones typically contain 20-35 vol% of near-spherical 0.5- to 2.0-cm vesicles. The size vesicles may decrease or increase upward in individual vesicle zones; however, the overall size of vesicles increases downward in the lava crust (Figure 14). In addition, the top 2-4 m of the lava crust sometimes contain distinct horizons of gas blisters that are interconnected by parting surfaces.

4.2.2. Jointing styles. Jointing in the Roza lava is generally characterized by uneven tapering columns and no distinct entablature. However, three main jointing patterns are identified based on column morphology, joint spacing and joint orientation: the columnar, crustal, and platy zones (see section

3.3 for definitions). The lower one-half to two-thirds of individual lobes is columnar and is characterized by uneven to regular, 1.5- to 4-m-wide, four- to five-sided columns (Figure 14). The columns are commonly split into 3- to 6-m-high blocks by discontinuous subhorizontal joints, and the columnar joints normally dissipate by bifurcation in the lowest ~0.3 m of the lobe. The upper one-half to one-third of individual lobes compose the crustal zone, characterized by uneven tapering columns, bounded by irregular joints typically spaced at 0.5 to 1.5 m, and often split by discontinuous subhorizontal cracks. The top 0.5-1 m sometimes feature short regular prismatic flow top joints as seen in pahoehoe lobes elsewhere [e.g., see *Chitwood, 1994, Figure 11*]. At the boundary between these zones, every second or third joint in the crustal zone merges with the joints of the columnar zone, while the rest terminate abruptly. This transition occurs at about the same level (± 1 m) as the continuous horizontal vesicle sheets appear in the lava. Joint propagation direction indicators in the Roza lavas indicate downward joint propagation at this level in the flow, implying that one out of two to three crustal joints continued its growth as a columnar joint. The down-

ward and upward growing joints meet about one third of the way up from the flow base (Figures 6, 8, and 10).

Platy zones occur as 0.2- to 1.0-m-thick horizons of closely spaced horizontal platy joints, splitting the lava into 2- to 20-cm-thick and 20- to 200-cm-long plates that show well-developed internal flow banding paralleling the joints. Platy zones are common in the Roza lavas and frequently occur just below or at the boundary between the columnar and crustal zones. They also occur in the lowest 1-2 m of thick (≥ 20 m) flow lobes (e.g., Figures 6 and 8). The order of joint formation is best observed at localities RDV, RSF, and RBL, where a platy zone occurs at the boundary between the crustal and the columnar zones. One-half to two-thirds of the crustal joints dissipate at the top of the platy zone. The throughgoing crustal joints crosscut the platy zone and continue below as columnar joints. The outline of individual plates can be traced on both sides of the gaping crustal joint indicating that the plates were split by the crustal joints. This is further confirmed by the matching fracture patterns on the opposite fracture surfaces. These relationships indicate that the platy joints were formed at about the same time that the downward

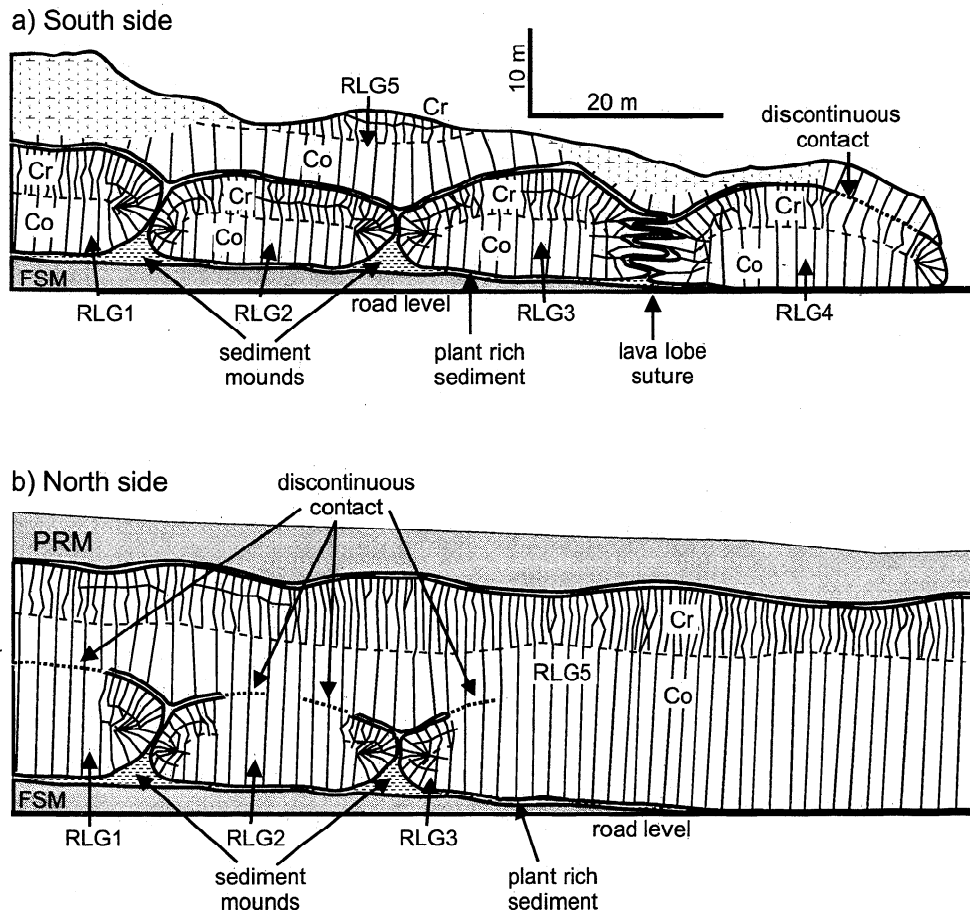


Figure 13. Field sketches showing arrangements of Roza flow lobes at Lyle (RLG on Figure 1). (a) Outcrop on south side of Highway 14. Lower lobes (RLG1-4) rest on partly carbonized plant-rich deposit and in places are separated by mounds of the same material. Overlying lobes (RLG5) fill in the low at boundary of lower lobes. (b) Outcrop on north side of Highway 14. Contacts of lobes RLG1-3 are distinct in lowest part of outcrop but become discontinuous (dot dashed lines) when followed up section, and lobes RLG1-3 merge with lobe RLG5. Lobe RLG4 is not present in this outcrop. Dashed line shows boundary between lava core (Co) and upper lava crust (Cr). Underlying lava (FSM) is a Frenchman Springs Member flow, and overlying lava (PRM) is a Priest Rapids Member flow, which has been removed by erosion in the south outcrop. Vertical and horizontal scales are indicated and both sections are drawn as viewed from the north. See text for further descriptions.

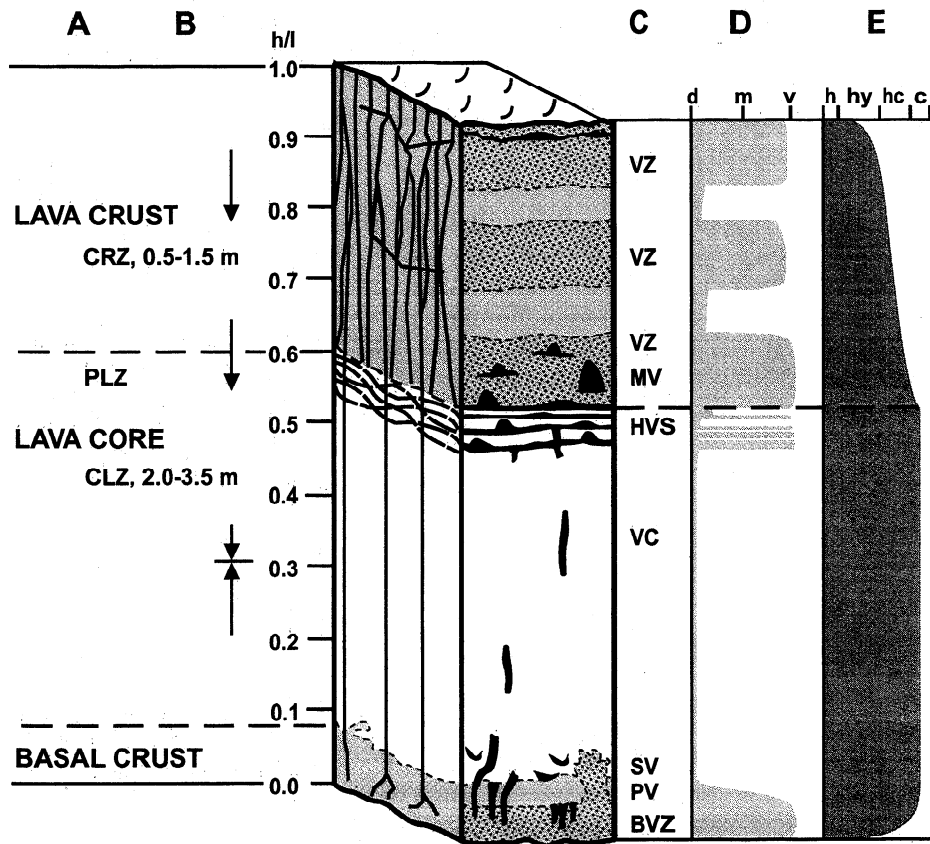


Figure 14. Composite graphic log illustrating characteristic structures of Roza sheet lobes, based on all exposures examined. Left side of column shows the characteristic three-part division of sheet lobes (A) and jointing styles (B). Right side shows distribution of vesiculation structures (C), vesiculation (D), and degree of crystallinity (E). The scale h/l indicates normalized height above the base of the sheet lobe (h , height in lobe; l , total lobe thickness). Column D gives amount of dense, d (0-5 vol% vesicles), moderately vesicular, m (10-20 vol%), and vesicular, v (30-40 vol%) lava. On Column E, h , hyaline; hy , hypohyaline; hc , hypocrySTALLINE; c , holocrystalline lava textures. See Figure 6 for key to other abbreviations.

propagating crustal joints reached this level in the flow, suggesting that the joints in the crustal zone formed first, followed by the joints of the platy zone, and, finally, by those of the columnar zone.

4.2.3. Petrographic texture. The bases of Roza sheet lobes are sharp, featuring smooth and billowy pahoehoe surfaces, with stretched glass fibers and small elongated vesicles. The quenched selvage of the basal crust is normally 0.5 to 2.0 cm thick and consists of hypohyaline lava with 25-30 vol% crystals in a sideromelane glass groundmass [Thordarson and Self, 1996a, Figure 6]. The mineral assemblage consists of plagioclase (~20%), clinopyroxene (~4%), and olivine (~3%). Mineral oxides are either absent or present in very low abundance (<0.15%). Phenocryst abundance is 5-12%; the remainder is groundmass size crystals (<0.2 mm). Glassy quenched Roza dike selvages and near-vent scoria clasts have identical phenocryst modes but do not contain the groundmass crystal-size population (Figure 15). The groundmass glass of the lava selvages is enriched in TiO_2 (~0.7 wt%) and FeO (~1.8 wt%) compared to the bulk lava composition (Table 3). Crystal fractionation calculations indicate that this change in composition can be acquired by ~20% crystallization (plagioclase ~12%, olivine ~2%, and clinopyroxene ~3%) of the initial lava composition. This evidence suggests that 15-20% crystallization occurred during lava transport [Thordarson, 1995; Thordarson et al., 1996]. The crystallin-

ity of the lava selvages increases slightly with distance from source but only by $\leq 10\%$ over ~200 km (Figure 15). The basal crust grades upward into hypocrySTALLINE rock, becoming progressively more crystalline toward the top and transforms sharply into holocrystalline lava core at 0.1 to 0.60 m above the flow base (Figure 14).

The lava core of Roza sheet lobes consists of fine-grained holocrystalline lava. In relatively thin lobes (≤ 15 m) the lava core tends to be diktytaxitic, with as much as 20 vol% of intercrystalline microscopic voids often filled by secondary minerals. However, diktytaxitic voids are absent in cores of thicker lobes. In thin section the groundmass mineral assemblage features an intergranular texture with subhedral to euhedral plagioclase, pyroxene, olivine, and $FeTi$ oxides, with $\leq 5\%$ modal glass mesostasis of rhyolite composition (Table 3).

The crystallinity of the upper crust ranges from hypohyaline to hypocrySTALLINE (e.g., Figure 14). The original flow tops of Roza sheet lobes feature smooth pahoehoe surfaces and subcentimeter thick glassy selvages (Figure 16a). Approximately the top third of the crust is hypohyaline with either a dark brown sideromelane glass or a black opaque tachylite matrix. Below this level, the crust is hypocrySTALLINE, and crystallinity increases progressively down to the lava crust/lava core boundary, where the ratio of glass mesostasis to crystals is ≤ 0.15 . The crystallinity of the mesostasis de-

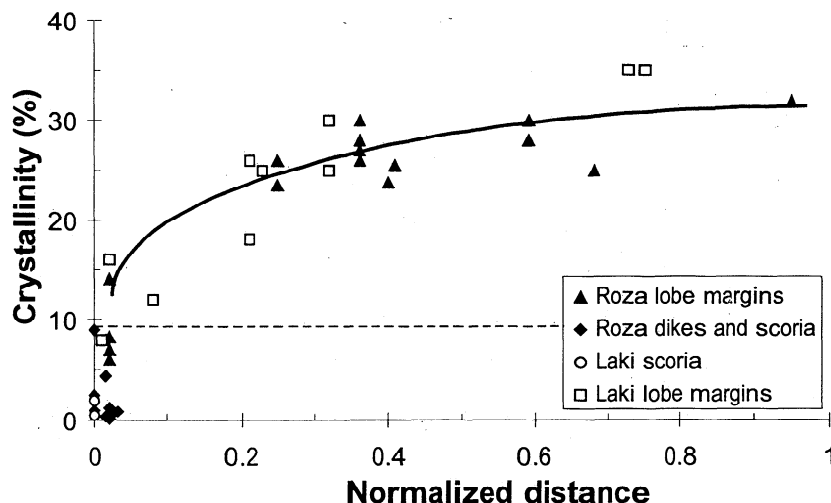


Figure 15. Variation in crystallinity of quenched Roza sheet lobe margins with distance from source. Also shown are data of quenched sheet lobe margins of the 1783 Laki lava flow [Thordarson *et al.*, 1996]. Distance is normalized to maximum length of each lava flow field, which is taken as 330 km for Roza [Tolan *et al.*, 1989] and 65 km for Laki [Thordarson and Self, 1993]. Crystallinity of glassy (quenched) dike margins and scoria clasts is also shown. Solid line is the inferred change in crystal content with distance; dashed line shows the estimated preeruption crystal content of the Roza lavas.

creases downward in the crust, and its chemical composition ranges from basaltic andesite to dacite composition, bridging the gap between the compositions of the groundmass glass in the lava selvages and the interstitial glass in the lava core (Table 3). A distinctive feature of the mineral assemblage in the lava crust is the dendritic form of the FeTi oxide phases in the mesostasis in the upper third of the crust. Below that level the crust is characterized by skeletal FeTi oxides, with a gradual change to euhedral crystal shape in the oxides in the lava core (Figures 16b-16d).

4.3. Other Key Observations

The structure shown on Figure 17a (locality RFS) was thought to be a spiracle produced by steam induced fracturing [Waters, 1960; Mackin, 1961], however, our observations show it is a suture between two sheet lobes. Such a suture also occurs between lobes on the north side of the Frenchman

Springs Coulee and between lobes at locality RLG (Figures 12 and 13). The sutures consist of interleaved subhorizontal lava plates which thicken toward and connect to the coherent lava on either side. The plates are bounded by glassy surfaces that are often striated (Figure 17b). These striations are orientated perpendicular to the strike of the suture, showing that the plates were formed as a succession of lateral protrusions from the interior of the lava on either side. The lava plates often feature stretched vesicles aligned parallel to the margins of the plates as well as pipe vesicles and small vesicle cylinders inclined toward the center of the suture. Subhorizontal cracks that originate at the junction of two plates extend into the coherent lava and show that the formation of these plates was associated with vertical extension of the lava lobe.

At locality RDV (Figure 1), sheet lobe RDV1 rests directly on a 0.35- to 0.75-m-thick layer of coarse scoria lapilli that originated from local rootless explosions in the Roza lava [Thordarson, 1995]. Hence the lobe RDV1 advanced over a

Table 3. Representative Analyses of Whole Rock and Groundmass Glass in Roza Eruptives

Sample Type	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total
Whole Rock	51.12	3.20	13.75	13.71	0.23	4.44	8.83	2.78	1.25	0.68	99.98
N = 469	0.64	0.10	0.39	0.76	0.03	0.35	0.37	0.18	0.15	0.07	0.31
Dike Margins	51.45	3.40	12.80	14.46	0.25	4.07	8.32	2.73	1.36	0.75	99.64
N = 255	0.29	0.02	0.19	0.17	0.01	0.12	0.10	0.08	0.06	0.08	0.24
Scoria	51.43	3.31	13.05	14.96	0.21	4.13	7.81	1.84	1.44	0.78	99.13
N = 4	0.02	0.10	0.18	0.32	0.01	0.01	0.12	0.13	0.09	0.02	0.27
Lobe Margins	51.47	3.86	12.08	15.73	0.26	3.51	7.87	2.21	1.47	0.91	99.47
N = 39	0.42	0.17	0.33	0.49	0.03	0.44	0.58	0.56	0.30	0.09	0.57
LCR-H-gl	54.84	1.95	12.85	13.43	0.24	1.75	6.96	3.62	2.16	1.54	99.47
N = 4	2.30	0.49	1.79	1.49	0.06	0.79	0.68	0.79	0.54	0.29	0.59
LCR-HC-gl	59.12	1.34	12.06	10.99	0.22	0.54	4.08	2.87	3.38	0.86	95.63
N = 4	0.68	0.17	0.67	0.87	0.03	0.09	0.46	0.29	0.42	0.62	0.72
LC-I-gl	72.50	0.72	14.01	2.44	0.03	0.05	0.84	4.51	4.41	0.15	99.72
N = 9	0.59	0.13	0.61	0.31	0.02	0.02	0.14	0.76	0.91	0.07	0.79

LCR-H-gl, groundmass glass of hypohyaline crust, 8.75 m above base of flow; LCR-HC-gl, groundmass glass of hypocrySTALLINE crust, 6.5 m above base of flow; LC-I-gl, interstitial glass in holocrystalline core, 2.75 m above base of flow; N, number of analyses. The standard deviation is given as 2σ . Whole rock analyses from Martin [1991] and groundmass glass analysis from Thordarson [1995].

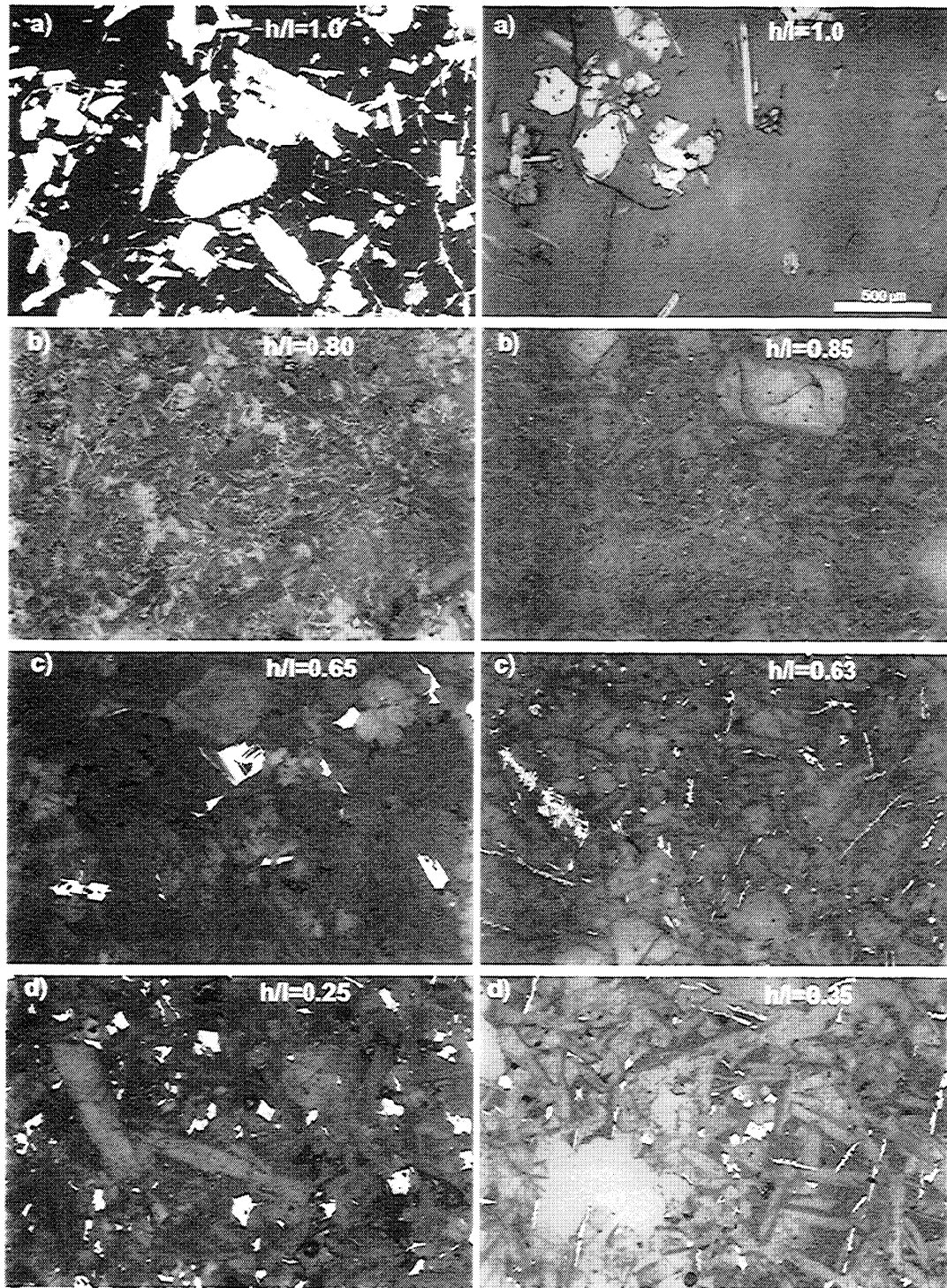


Figure 16. Photomicrographs of lava from Roza and Kilauea, Hawaii, sheet lobes in thin section comparing the morphology of FeTi-oxides. Microscope setting is reflected light and 30x magnification. Scale bar is shown on top right of photos. Left column a-d, a 12 m thick Roza sheet lobe RFS1 at Summer Falls (Table 2); right column a-d, a 2.7-m-thick sheet lobe from the 1990-1991 Kalapana, Kilauea, lava flow field (Table 4). Each column represents a transect from (a) the quenched flow top selvage, through (b) and (c) the upper lava crust, to (d) the lava core. The h/l values indicate normalized height above the base of each sheet lobe (h , height in lobe; l , total lobe thickness). Note that in both examples the top lava selvage (Photos a) is free of FeTi oxides but the oxides occur as minute dendrites in the upper part of the lava crust (Photos b), as larger dendritic to skeletal crystals in lower part of the lava crust (Photos c), and as predominantly euhedral complete crystals in the lava core (Photos d). The silicate minerals are plagioclase, pyroxene, and olivine. See text for further discussion.

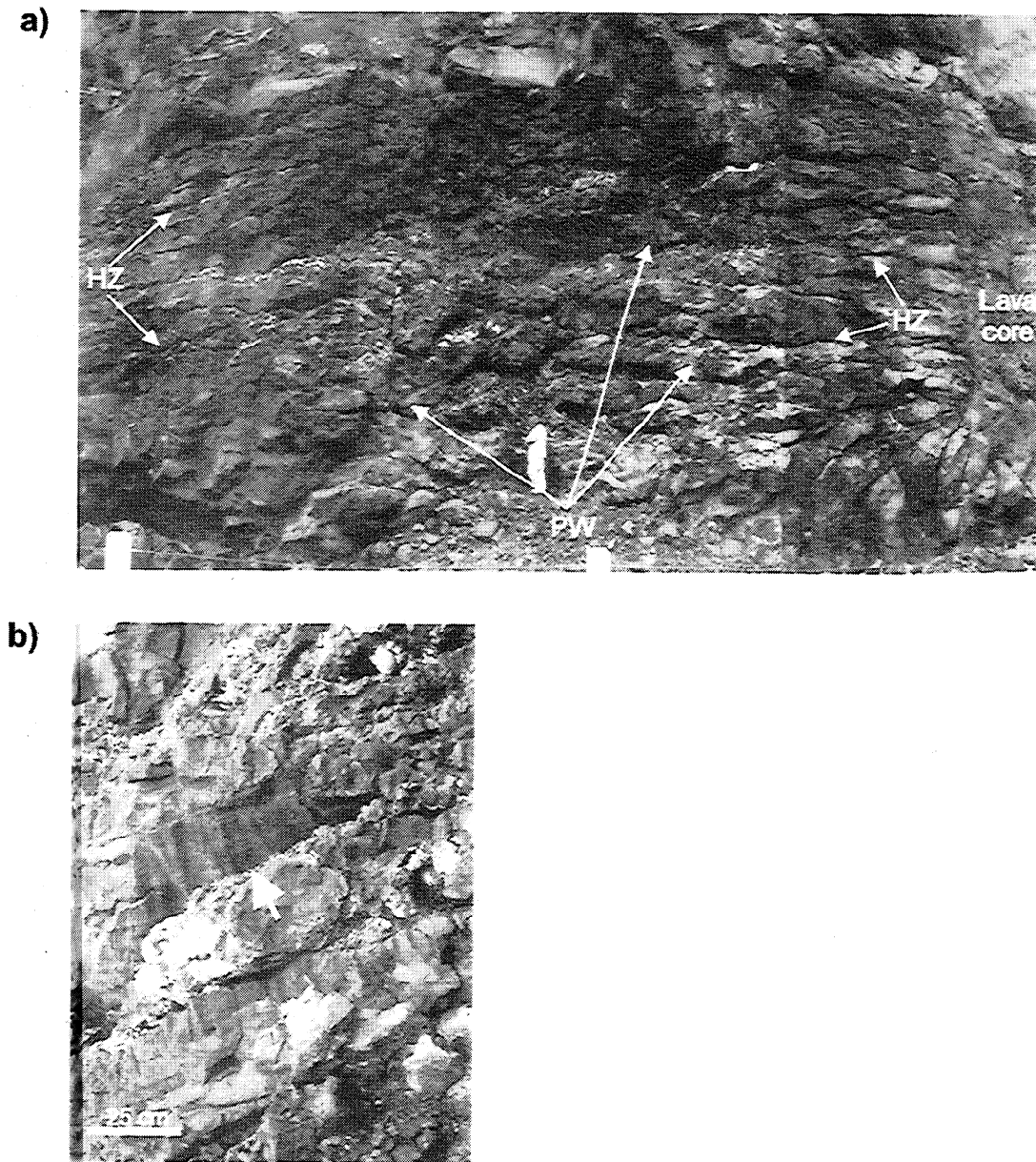


Figure 17. (a) Large lava lobe suture in Roza lava (note person for scale) at Frenchman Springs Coulee (RFS on Figure 1). Abbreviations are PW, interleaved sub-horizontal wedge-shaped plates of lava; HZ, sub-horizontal cracks extending in to massive lava core on either side. (b) Striations and grooves on the basal (arrow) surface of a plate. See text for further discussion.

surface that was covered by unconsolidated scoria and has in situ scoria clasts as small as 0.5 cm imbedded into the basal surface of lobe RDV1 and partly draped by the lava (Figure 18a). The flow base is also strongly convoluted around bombs, and the lava did not incorporate clasts or erode the unconsolidated scoria.

At locality RHB (Figure 1 and Table 2), the Roza Member features a 2- to 4-m-thick package of compound pahoehoe lobes overlain by a 39-m-thick sheet lobe (Figures 10 and 18b). Lobe contacts are annealed and the package merges with the coherent sheet lobe above. Adjacent to this package are isolated 0.2- to 0.5-m-thick pahoehoe lobes of Roza lithology completely imbedded in a sandstone unit capping the Ellensburg Formation. These lobes have a thick glassy selvage and ropy surfaces, while the sediment surrounding them is baked and contains ~2-mm-wide vesicular pipe-like

features that radiate outward from the lobe margins. The pipes indicate that the sediment was soft and moist when the Roza lava flowed over it. In the top 1-2 m of the Squaw Creek Formation the sediment immediately surrounding the lobes is contorted and disturbed, but otherwise the original sedimentary structures are undisturbed. Despite the interaction of lava and moist sediment, the flow lobes are bounded by smooth pahoehoe surfaces, and there is no evidence for physical mixing between lava and sediments or for flow-driven erosion or plowing by the lava.

5. Discussion

5.1. Origin by Series of Eruptions?

Martin [1989, 1991] proposed earlier that the Roza consists of several rapidly emplaced (days to weeks) lava flows

produced by a series of eruptions. In this first subsection we review the evidence used to substantiate this hypothesis. Martin used the flow unit distinction, coupled with the change in whole rock compositions, to divide the Roza Member into six chemical subtypes of regional extent. The geochemistry does not provide conclusive evidence for separate eruptions because of the narrow range of the Roza lavas. The subtypes are comagmatic and define a continuous compositional trend that became slightly less evolved over time (Figure 2). The compositional variability of the Roza Member does not ex-

ceed that of other CRBG lava flows [e.g., *Wright et al.*, 1973, 1989; *Swanson and Wright*, 1980; *Mangan et al.*, 1986; *Martin*, 1991] or that of other, smaller Holocene flood lava eruptions recognized for their homogenous magma composition [*Thordarson et al.*, 1996, *Thordarson and Self*, 1996b]. Martin also suggested that each chemical subtype is a single flow (cooling) unit that was emplaced by a short-lived eruption. This conclusion is not entirely consistent with the established stratigraphy because at about one third of the localities, individual subtypes consist of two or more flow units (Figure 1

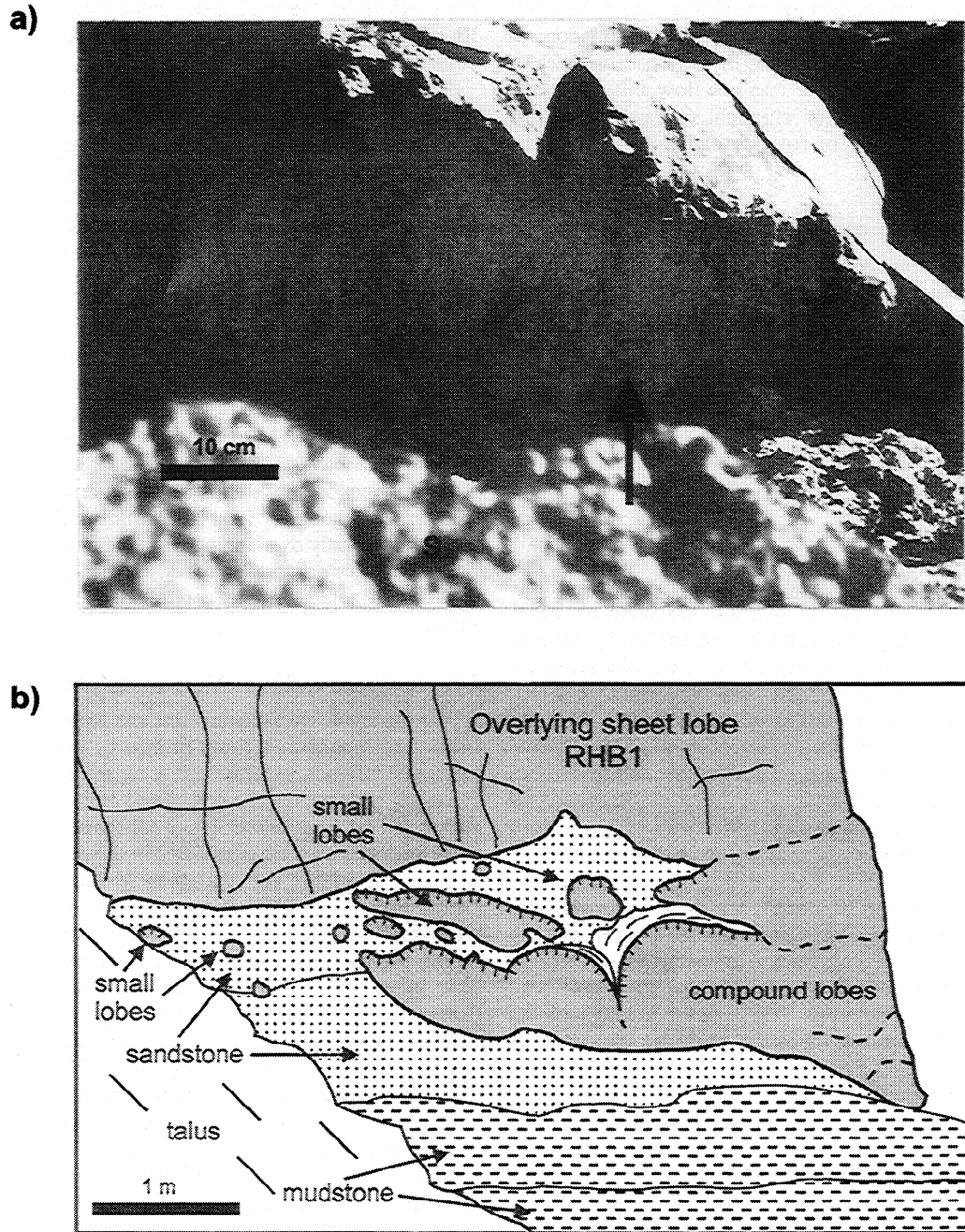


Figure 18. (a) Smooth pahoehoe flow bottom of a Roza sheet lobe RVD1 at locality RVD (Figure 7a) resting directly on a scoria bed (S), formed by rootless eruptions close by. Note how the basal surface drapes small clasts embedded into bottom surface. (b) Field sketch from locality RHB (Figure 1), showing a compound lava lobe package and isolated small lobes at the base of a 39-m-thick sheet lobe (RHB1). Small lobes invaded the top two fluvial sandstone beds of the Ellensburg Formation but not the underlying diatomaceous mudstone. Lobe contacts in this compound package are annealed (dashed lines), and farther up, they merge with the base of the overlying sheet lobe. Hatchured lines indicate surface of lobes.

and Table 2). These occurrences cannot be simply explained as flow margin features because they are found at localities both central and close to the inferred boundaries of each subtype (e.g., sections RCCL, RRL-6, DC-15, RRL, RCD). These internal flow units normally cannot be traced to adjacent sections (e.g., localities RBLB-RSF and RRL-RCF). Thus the "flow (cooling) unit" criterion does not support the idea that the chemical subtypes correspond to individual lava flows produced by separate eruptions, unless each subtype involved more than one eruption. On these grounds, we also dispute the validity of the subtype divisions IA-IB and IIA-IIB. Their petrographic and chemical characteristics are virtually identical; the differences are practically within the limits of analytical error (Figure 2). Again the "flow unit" concept cannot be used as the basis for this division because each of these subtypes consist of more than one flow unit (Figure 1). Consequently the number of chemical subtypes within the Roza Member may only be four, as originally proposed by Martin [1987].

5.2. Product of One Eruption?

The chemical homogeneity of the Roza lavas, in our opinion, favors a single eruption, especially when it is considered that no significant time breaks are identified within the Roza Member. This is demonstrated by the preservation of delicate pahoehoe surface structures between lobes of different subtype compositions and by an absence of sedimentary interbeds or erosional surfaces within the Roza succession. This implies that a very short time interval passed between the emplacement of successive chemical subtypes, but does not explicitly prove one continuous eruption. More conclusive evidence is obtained from a Roza feeder dike at locality RRG and the near-vent successions at locality RWI (Figure 1).

One of the composite Roza dikes features subsequent injections of subtypes I and II magmas. Assuming an initial width of 5 m for this composite dike and cooling by conduction, it would have taken ~4 months for the initial subtype I dike to solidify [Turcotte and Schubert, 1982, equation 4-143, p. 173]. Since the subtype I dike was partly molten when the subtype II magma was injected (see section 4.1), the period of 4 months can be taken as the maximum time that passed between termination of flow in the first injection and the second intrusion. The logical conclusion is that the subtypes IA and IIA magmas were produced during the same eruption.

At locality RWI, where the near-vent succession consists of chemical subtypes II, III, and IV, the stratigraphic relationships do not reveal any significant time breaks between the formation of each subtype; rather, they suggest intermittent accumulation of pyroclastics and lavas that may have been erupted from the same vents. The interstratification of the small subtype II pahoehoe lobes and of the scoria deposit at the base of the RWI section shows that they were erupted concurrently, although the emplacement of lava must have preceded the scoria deposition by a small amount of time. While the horizontal bedding and the grain size of the scoria are consistent with its origin as a proximal fall deposit, the irregular surface topography, the lava-filled cracks, and the truncated bedding in the scoria deposit cannot be explained by simple air fall deposition. However, field relations suggest that the scoria was deposited onto a moving lava flow, which may explain the mounds and the cracks. A similar situation developed during the 1991 A.D. Hekla eruption, where 5-10 m of scoria fall deposit were deposited onto the surface of a slowly moving proximal lava flow [Gudmundsson *et al.*,

1992; T. Thordarson, unpublished data, 1998]. The movement of the underlying lava resulted in formation of tensional cracks up to 4 m wide and 10 m deep in the unconsolidated scoria. Initially these cracks were bounded by vertical walls of unconsolidated scoria, but because of slumping the cracked pile gradually evolved (<2 years) into series of elongate rolling scoria mounds and elongate ridges. Identical structures occur within the 1783-1784 Laki lava flow up to 1 km from the vents, where 5-m-thick scoria deposit rests on the proximal lavas. Using the Hekla analogy, several months, or possibly up to a year, may have passed before the overlying Roza units (i.e., subtypes III and IV) covered the scoria pile at Winona. However, the gradational contact between the subtype III spatter deposit and subtype IV clastogenic lava suggests continuous emplacement.

The evidence given above indicates a near-continuous emplacement of subtypes I and II lavas and pyroclastics, as well as of subtypes III and IV. Our data also suggest that the eruption of subtypes II and III magmas cannot have been separated by more than a few years, which is well within the our 14-year estimate for the duration of the Roza eruption [Thordarson and Self, 1996a]. Thus we conclude that the Roza Member lava flows were produced by one long-lasting eruption. The composition of the Roza magma changed gradually over time and chemical subtypes are confined to certain sectors of the lava flow field. We suggest that the individual chemical subtypes (I-IV) correspond to our usage of the term lava flow (see section 3.3) and were emplaced during separate episodes of the same eruption [see Self *et al.*, 1997, Figure 14]. In this respect it is interesting that the vertical arrangement of the Roza subtypes is consistent with the internal geometry of an inflated pahoehoe flow field [e.g., Mattox *et al.*, 1993; Self *et al.*, 1996a]. Partly overlapping but parallel lava flows are produced by major eruption episodes, and the distribution of later flows is to a large extent controlled by the earlier formed lavas.

5.3. Significance of Lava Morphology and Structures

Various evidence indicates that the Roza flow field consists of compound lava flows formed by insulating emplacement and inflation processes. If analyzed in isolation, these pieces of evidence may be considered ambiguous or could be written off as local anomalies. A different picture emerges, however, when they are considered in their entirety.

5.3.1. Evidence for the Roza Member being a compound lava flow field. Several lines of evidence indicated the compound nature of the Roza Member. One is the observed vertical and lateral arrangement of small and large flow lobes within individual chemical subtypes (i.e., lava flows). Individual subtypes consist of two or more large, superposed sheet lobes at 11 localities, and abutting sheet lobes occur at three localities (e.g., Figures 11-13). The compound character of Roza is further corroborated by occurrence of small (<5 m thick) lobes occurring at the base and on the surface of large sheet lobes at localities RHG, RDV, RDC, RHB, RSL, and RKG (Table 2). Occurrences of annealed and discontinuous lobe contacts are yet another indication for the compound character of the Roza lavas [e.g., Walker, 1972].

The compound nature of Roza lavas is also indicated by the wide range in flow lobe thicknesses (0.4-52.0 m) and by the skewed frequency distribution, which shows that <25-m-thick flow lobes are most abundant within the Roza Member. High frequency of 10- to 25-m-thick lobes reflects the abundance of sheet lobes within the Roza Member. Their aspect

ratios (V/H [Walker, 1972]) is of the order of 0.02-0.2 in the few outcrops where they could be measured. The aspect ratios of sheet lobes in much smaller Holocene and historic pahoehoe lava flow fields are similar [e.g., Walker, 1991; Hon *et al.*, 1994; Rossi and Gudmundsson, 1996]. The erratic distribution in thickness values of the Roza Member and individual chemical subtypes implies that the advance of the Roza lavas was controlled by its own lobe construction rather than larger topographic features such as valleys or ridges.

5.3.2. Evidence for growth of the Roza as inflated pahoehoe flows. Sheet lobes are volumetrically the most significant component of the Roza Member, and such lobes are an integral component of inflated pahoehoe flows [Hon *et al.*, 1994]. These should not be confused with ponded flows which have distinctly different morphology and structure [Self *et al.*, 1998]. Tumuli occur on Roza lavas at localities RWI, RDV, and RFS are the most diagnostic structure of inflated pahoehoe lavas [Walker, 1991; Rossi and Gudmundsson, 1996]. Other flow structures that indicate inflation was operating during emplacement of the Roza lava are as follows: (1) The lava lobe sutures that occur at localities RFS and RLG. Identical, but smaller, sutures in other compound pahoehoe flow fields are formed where two abutting lobes inflate and thicken together [Walker, 1991; Self *et al.*, 1997a]. (2) The steeply dipping flow or cooling surfaces observed at localities RDV and RDC that terminate abruptly within the lava and represent the merging of several smaller lobes to form a larger sheet lobe which subsequently thickened by inflation (Figure 19a). (3) The small pahoehoe lobe packages between the larger sheet lobes at localities RHG and RDV and their contact relationships to the underlying lobe which indicate that they were formed as surface breakouts, which are diagnostic of inflated lavas [Walker, 1991; Mattox *et al.*, 1993; Chitwood, 1994; Hon *et al.*, 1994; Self *et al.*, 1997]. The change from distinct to discontinuous lobe contacts at localities RSL, RHB and RLG can also be explained if the lowest lobes were formed as lobe margin breakouts as illustrated in Figure 19b. (4) The Roza lavas are not truly flat-top flows. Individual flows pinch and swell along the length of an outcrop because the lower and upper surface undulations are typically out of phase. Other CRBG pahoehoe lavas show similar characteristics in a cross-section [Self *et al.*, 1997], and although this feature cannot be regarded as direct evidence of inflation, it is consistent with observed surface undulations on inflated Holocene pahoehoe lavas. (5) Horizontally oriented tree molds between Roza lobes at localities RBL and RSL are best explained by inflation. Horizontal tree molds are very common in inflated pahoehoe lavas in Hawaii and are formed when a standing tree is surrounded by a relatively thin, inflating flow lobe (Walker [1995] and observations by the authors at Kalapana in Hawaii). The lowest part of the trunk is in contact with the hot lava and burns slowly, and the remainder of the tree, left unsupported, falls onto the solid surface of the inflating lobe. As inflation progresses, the now horizontal trunk is lifted farther away from its original growth surface and eventually is covered by a later flow lobe.

5.3.3. Gradual emplacement. Structures indicative of gentle and slow advance of the Roza lava occur at a number of localities. Field evidence shows that on a number of occasions the Roza lavas flowed over either unconsolidated scoria deposit, sediment, or rubble (i.e., localities RUF, RVR, RPO, RDV, RSC, RHB, RLG, RDC). However, these unconsolidated deposits show no evidence of being eroded, plowed, or picked up by the overlying lava, as one might ex-

pect if the flow was moving at the velocities (>10 m/s) predicted by models assuming rapid turbulent or laminar emplacement of the lavas. On the contrary, the smooth basal pahoehoe surfaces gently drape decimeter-size irregularities and feature impregnated centimeter-size clasts from the underlying deposits (Figure 18a). At locality RHB where the Roza lava invaded water-saturated, low-density lacustrine/fluvial deposits, the lava consists of coherent pahoehoe lobes, and there is no evidence of physical mixing between the invading lava and the sediments. The observed sediment deformation structures are more in-tune with density-driven sinking of lava into soft sediments and simultaneous squeeze up of deposits. Similar relationships are observed at localities RFS and RPO, where unconsolidated, low density lacustrine deposits are invaded by coherent Roza pahoehoe and pillow-shaped lobes and overlain by several meters thick peperite horizons [e.g., Swanson *et al.*, 1979].

Furthermore, preservation of delicate pahoehoe rope structures and tree molds on surfaces between lobes is inconsistent with rapid emplacement of the Roza lavas. The thin surface-fed lava fingers that invaded cracks and voids in the surface of underlying lobes are also good indicators of slow emplacement. It is unlikely that a fast moving flow would have produced such structures without eroding the substrate. In our view, all these features are more consistent with slowly advancing lava rather than a rapidly flowing, possibly turbulent flow.

5.4. Internal Lava Flow Structures and Evidence for Origin by Inflation

We have shown that the overall aspects of the internal structures in Roza sheet lobes are identical regardless of whether they occur in near-vent exposures or distal outcrops up to 300 km from the source (e.g., Figures 5, 6, 8 and 10). We have also shown that vesiculation pattern, jointing style, and petrographic textures in Roza sheet lobes change systematically in a vertical section and define a three-part structural division of the lobes: the basal crust, the lava core, and the lava crust. This three-part division of internal structures is also characteristic of sheet lobes from other pahoehoe flow fields that we have studied, including other CRBG lavas and several small to medium size lavas in Iceland and Hawaii (see Figure 20). Parameters and structures of sheet lobes from these pahoehoe flow fields are compared in Table 4. The universality of this three-part structural division of pahoehoe sheet lobes is clearly demonstrated by these examples, and we now discuss how it confirms an origin by inflation.

In Roza sheet lobes, segregation vesicles, pipe vesicles, and/or small vesicle cylinders occur in the basal vesicular zone and the lava core. Similarly, horizontal vesicle sheets and associated megavesicles occur consistently at the base or right below the vesicular flow top in the lobes, and traces of vesicle cylinders are found in the lava core of most lobes examined. Vesicle cylinders and horizontal vesicle sheets are formed by segregation and collection of volatile-rich fluids into pipes, and the current consensus is that this process is a strictly postemplacement phenomenon, formed in a cooling flow [e.g., Goff, 1996]. The genetic relationships of these structures are not particularly well preserved in Roza lavas, but their overall aspect and position are strikingly similar to that found in other pahoehoe sheet lobes (Figure 20), such as the Levering lava, where genetic relationships are exceptionally well preserved [Thordarson, 1995].

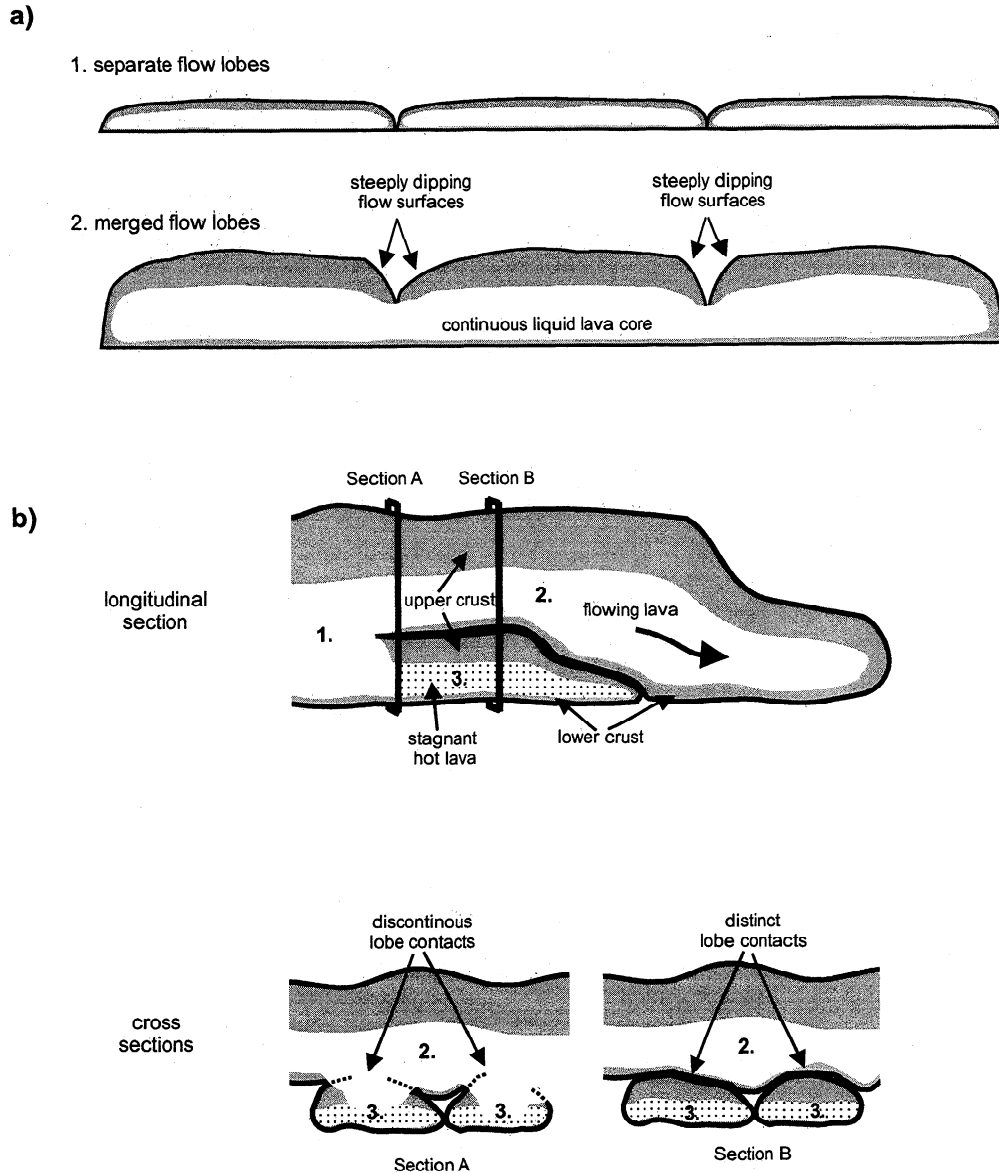


Figure 19. (a) Sketch illustrating formation of hanging and steeply dipping flow surfaces on three abutting flow lobes, bounded by distinct flow surfaces on all sides (stage 1). Each lobe has an upper and lower crust (shaded) and a liquid lava core (white). These lobes are inflating and spreading, and eventually merge to form a single lobe due to coalescence of the liquid lava cores (stage 2). The end result is a sheet lobe with a continuous lava core, featuring several steeply dipping flow surfaces that terminate near the top of the core. (b) Sketch showing an inflating sheet lobe overtaking an earlier emplaced, but now stagnant, frontal breakout. Such occurrences can explain the change from distinct to discontinuous contacts in the same outcrop. Depending on the location and orientation of the vertical cut of the outcrop, lobe boundaries can occur either as distinct flow surfaces or as discontinuous contacts as demonstrated by cross sections A and B. Identical contact relationships are observed within the currently active Pu'u 'O'o-Kupaianaha, Kilauea, lava flow field where sheet lobes overtake earlier formed frontal breakouts (T. Mattox, personal communication, 1998).

Vesicle cylinders originate within the basal vesicular zone as centimeter wide pipe vesicles and the small vesicle cylinders which coalesce to form larger cylinders higher up in the flow. The vesicle cylinders connect to the horizontal vesicle sheets at the top of the lava core, showing that the cylinders fed the sheets. In the lowest 1-2 m of the lava core the cylinders are often sharply inclined (30° - 80° from vertical) but then resume a near-vertical orientation farther up in the lava core, demonstrating that cylinders preserved in solidified lavas are formed as the moving lava was coming to halt or immediately thereafter. The Levering also contains clusters of

pipe vesicles and small vesicle cylinders that are truncated at the basal crust/lava core boundary and are often associated with stretched segregation vesicles, as found in the Roza. These structures show that the gas-rich segregation material was rising through these pipes during flow emplacement and was subsequently incorporated and removed by the flowing lava in the core above. This implies that formation of segregation pipes is a continuous process that is initiated during flow emplacement and is not strictly a postemplacement phenomenon as thought previously. Typical rise velocities for 3- to 10-cm-wide vesicle cylinders in basaltic liquid are of the

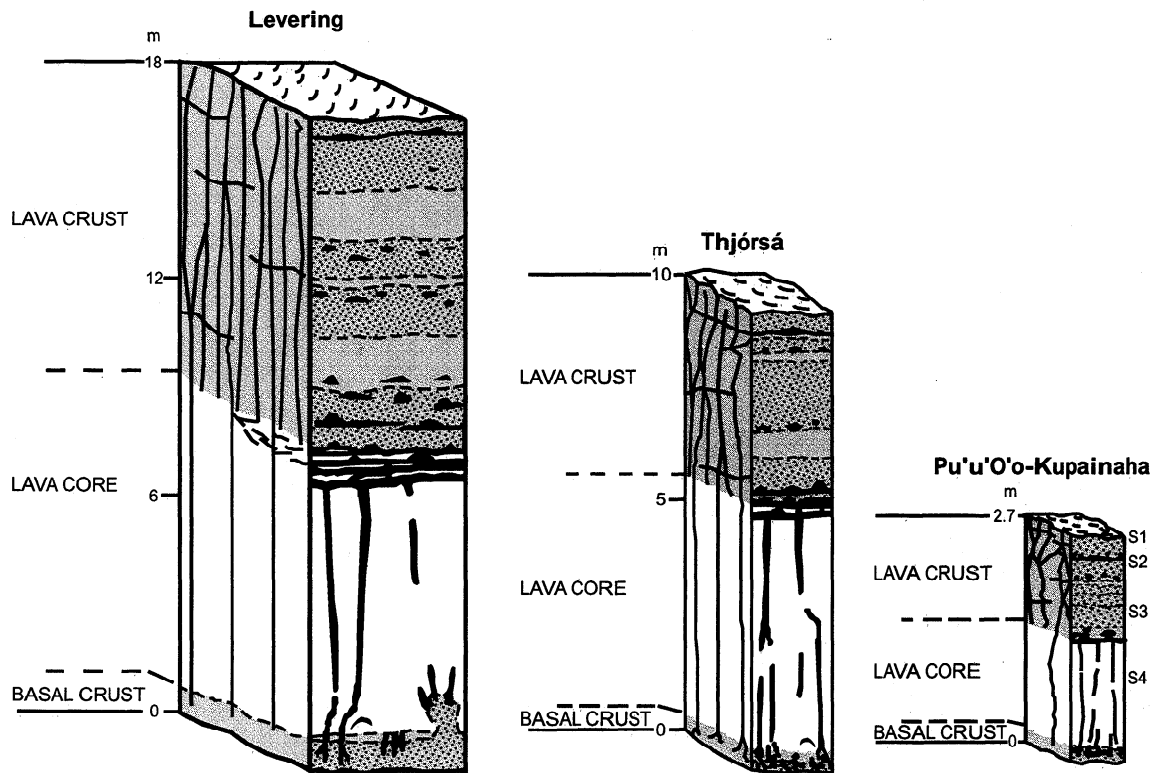


Figure 20. Examples of sections through sheet lobes from pahoehoe lava flows of vastly different sizes (see also Table 4). Section 1, an 18-m-thick sheet lobe of the Levering lava, Grande Ronde Formation of the CRBG, measured at Sentinel Gap, Washington. Section 2, a 10-m-thick sheet lobe from the Thjorsá lava. Section measured at Thjorsárbrú in southern Iceland. Section 3, a 3.6-m-thick sheet lobe from the 1990-1991 Kalapana flow field at Kilauea, Hawaii. Note the overall structural similarities of these flow units, although details vary, and all feature the characteristic three-part division of sheet lobes. The abbreviations, S1-S4, show locations of samples used for the photomicrographs on Figure 16.

order of 1-3 m/d [Goff, 1996], which is 10-30 times higher than the advance velocity of the downward propagating cooling front in a conductivity cooling lava [e.g., Wright and Okamura, 1977]. Thus the location of the solidification front at the time the flow of lava stopped should be just above the level where the cylinders are transformed to horizontal sheets. The position of the horizontal vesicle sheets is normally in the upper middle of each Roza sheet lobe (e.g., Figure 14), implying that a crust of considerable thickness had formed during flow emplacement. Consequently, the top of continuous horizontal vesicle sheets marks the boundary between the lava crust and the lava core at the time when the flow of fresh lava ended and the molten core became stagnant.

With a thick crust forming during flow emplacement, the alternating meter-scale horizontal vesicular and vesicle-depleted zones of the Roza lava crust record the progress of vesiculation during lava emplacement. The vesicular zones typically contain macroscopic spherical vesicles and may have formed either as the sheet lobe was depressurized by a sudden breakout or drop in lava supply [Cashman and Mangan, 1994; Cashman and Kauahikaua, 1997], or by periodic flow of more bubble-rich lava through the lobe. By either mechanism, bubbles accumulated rapidly to form a viscous bubble-rich horizon at the base of the crust. Previously, the formation of such horizontal vesicular zones in CRBG lavas was attributed to episodic bubble formation at the base of a stagnant flow [McMillan et al., 1989].

The difference between the jointing styles of the crustal and columnar zones in the Roza lavas indicates that jointing occurred in at least two stages, and the occurrence of platy joints at number of outcrops implies a third. Such multistage jointing along with the determined order of joint formation is easily explained in terms of inflating sheet lobes but is difficult to explain in terms of single-stage cooling, as is expected for a lava that came to rest in a fully liquid state. The uneven and relatively compact joints of the crustal zone are formed in the brittle part of lava crust by jostling of the crust during inflation. As the flow comes to a halt, these conditions are relaxed, and the stagnant lava core cools slowly in a homogeneous stress field [Aydin and DeGraff, 1988], explaining why only one out of two to three crustal joints continues to grow as columnar joints. As indicated by joint propagation directions, the upward and downward growing columnar joints usually meet near the center of the lava core, which is expected because the molten lava core is now enveloped by solid lava and the rate of cooling from the base and the top of the lava core should be roughly equal. The platy zones are always positioned in the lava core, normally at or near the boundaries with the upper and lower crust. The order of joint formation, orientation of platy joints, and flow foliation of the lava forming the plates suggests that platy zones were formed by horizontal shearing [Mackin, 1961]. As the flow of lava comes to halt, the semimolten lava core is bounded by solid crust at its top and base. A creeping flow in a now highly vis-

Table 4. Morphology and Structure of Sheet Lobes in Pahoehoe Lavas from Columbia River Basalt Group, Iceland and Hawaii.

Lava Flow	Age	Volume, km ³	Locality ^a	Lobe Thickness, m	Basal Crust Thickness, m	Lava Core Thickness, m	Lava Crust Thickness, m	Ratio h/l ^b	Emplacement time ^c , months	Surface ^d	Surface Features ^e	Internal Features ^f
Columbia River Basalt												
Levering, GRF ^g	15.6 Ma	>100	Sentinel Gap	17.4	0.4	8.8	8.2	0.51	15.39	phh	s	hz, mv, hs, vc, pv
Unnamed, GRF ^g	~16 Ma?	-	Bingen	21.1	0.1	12.9	8.1	0.61	15.02	phh-sphh	s	hz, mv, hs, vc, pv
Sentinel Gap, WF ^g	~15.3 Ma	1190	RSF	18.0	0.2	10.4	7.4	0.58	12.53	phh	l,s	hz, mv, hs, vc, pv
			RLG	25.0	0.2	14.8	10.0	0.59	22.89	phh	l,s	hz, mv, hs, pv
Iceland												
Eldborgir	9.2 ka	13	Thingvellir	4.7	0.1	1.9	2.7	0.40	1.67	phh	it, l, s, r,	hz, mv, hs, vc, pv
Thjórsá	8.5 ka	21	Thjórsárbrú	10.0	0.4	5.1	4.5	0.51	4.64	phh-sphh	it, s, r, is	hz, mv, hs, vc, pv
				11.0	0.3	4.6	6.1	0.42	8.52			hz, mv, hs, vc, pv
Krepputungur Eldgjá	~8 ka ~935 A.D.	>7 15.4	Upptyingar	14.0	0.4	8.3	5.3	0.59	6.43	phh-a'a (90/10)	it, l, s, r, is	hz, mv, hs, pv
			Hólmsá	8.2	0.4	5.0	2.8	0.61	1.79	phh-a'a (85/15)	it, l, s, r, is	hz, mv, hs, vc, pv
Laki ^g	1783-84 A.D.	14.7	Alviðruhamrar	>7	-	>3	4.1	-	3.85			hz, mv,
			Eldvatnsbrú	3.6	0.1	2.0	1.5	0.56	0.52	phh-sphh-a'a	it, r, l, s, is	hz, mv, hs, vc, pv
			Hellisá River	3.5	0.3	1.9	1.3	0.54	0.39	(35/45/20)		
Surtsey	1964-67 A.D.	0.4	Kambar	4.5	0.2	2.2	2.1	0.49	1.01			
			Surtsey	3.2	0.4	1.7	1.1	0.53	0.28	phh-a'a (95/5)	it, r, s, l, is	hz, mv, hs, vc, pv
Hawaii												
Kane Nui o Hamo	~0.6 ka	>2.0	Lae'apuki	3.8	0.1	1.1	2.6	0.29	1.55	phh	it, r, s, l, is	hz, mv, hs, vc, pv
Pu'u'O'o-Kupaianaha	1986-current	>1.0	Kalapana	2.7	0.2	1.1	1.4	0.42	0.45	phh	it, s, l,	hz, mv, hs, vc, pv

^aSources of data. Eruptions: Levering [Landon and Long, 1989]; Sentinel Gap [Tolan et al., 1989]; Eldborgir [Saemundsson, 1992]; Thjórsá [Vilmundardóttir et al., 1990]; Krepputungur [Thordarson and Self, 1996b]; Eldgjá [Miller et al., 1997]; Laki [Thordarson and Self, 1993]; Surtsey [Thorarinsson, 1968]; Kane Nui o Hamo [Holcomb, 1987]; Kupaianaha (Heliker et al., 1998). Location and measurements of sections are from Thordarson [1995] and T. Thordarson unpublished data, except localities LSG and RSF are shown on Figure 1a.

^bRatio of lava core thickness to total lobe thickness for each lobe; range between 0.29 and 0.61.

^cEmplacement time for each lava lobe, calculated using lava crust thickness and empirical equation of Hon et al. [1994]. See discussion in section 5.7.

^dLava surface morphology abbreviations are phh, pahoehoe; sphh, slabby pahoehoe; a'a, a'a flow top. Approximate proportions of each given in parenthesis. All lavas have a pahoehoe base.

^eSurface feature abbreviations are it, inflation tumulus; r, pahoehoe ropes; l, pahoehoe lobes; s, pahoehoe sheet lobes; is, inflation (lava lobe) suture.

^fInternal feature abbreviations are hz, horizontal vesicular zones; mv, megavesicles; hs, horizontal vesicle sheets; vc, vesicle cylinders; pv, pipe vesicles.

^gOutcrops exposing the interior of Laki lava are rare and these examples represent thin sheet lobes in the flow field. Up to 15-m-thick lobes are exposed, but outcrop is inaccessible for measurements.

cous lava is likely to induce horizontal stresses along the lava core boundaries because of a slight velocity gradient.

The Roza sheet lobes have a strongly asymmetric distribution of petrographic textures (e.g., Figure 14). This asymmetry in crystallinity suggests that the upper crust grew at rates that are orders of magnitude greater than the growth of the basal crust. If the Roza sheet lobes were initially deposited as 10- to 50-m-thick sheets of coherent liquid lava, then the variation in the petrographic textures should mimic those of stagnant lava lakes and the profile of petrographic textures in a 20-m-thick lava flow should have its symmetry plane at ~8 m above the base [Wright and Okamura, 1977; Hon *et al.*, 1994]. This is obviously not the case. However, vertical variations in petrographic textures appear to be consistent with inflation, because direct field measurements show that the base of inflating pahoehoe lobes cools at rates that are orders of magnitude slower than the top [cf. Keszthelyi, 1995].

This difference in the cooling rates of the upper and lower crust can be explained by steady flux of hot lava between two crustal layers, where one is a free boundary and the other is a fixed (stationary) boundary. The steady flow in the core brings hot lava in contact with the base of the upper crust, and the lava is subsequently cooled and accreted to the crust. This addition of material is accommodated by upward movement of the upper crust (inflation), which is possible because the upper surface of the lava crust is free to move. This process also implies that as new material is added to the base of the crust, the material added previously is effectively lifted and removed from contact with hot moving lava. As earlier crustal accretions are moved farther away from the hot molten interior, they are eventually cooled to temperatures of brittle behavior (~800°C [Hon *et al.*, 1994]). Upon contact with the ground the lava cools, and the basal crust may initially attain thicknesses of several centimeters to a few tens of centimeters. However, the lava base is a fixed boundary, and a continuous flux of hot lava over the basal crust is likely to maintain high temperatures at its upper surface and therefore hamper its growth during lava emplacement. It is possible that a balance is established between the growth of the basal crust and thermal deformation inflicted by the moving lava, which in turn may explain the consistent occurrence of thin basal crusts in sheet lobes.

Dendritic morphologies of FeTi oxides in samples from the upper third of the lava crust (Figure 16b) are compatible with the suggestion that hot liquid lava cooled rapidly below its solidification temperatures as it came in contact with the base of the crust. Thus a sharp thermal gradient existed across the boundary at the time, which caused undercooling of the hot lava. The coupled effects of heat conducted through the crust and the continuous introduction of hot liquid lava to the base of the crust helped to maintain these conditions during emplacement. However, the temperature difference across the boundary decreased gradually as the crust thickened and the rates at which heat was transferred through the crust were reduced. The progressive downward changes in the crystal habit of the interstitial FeTi oxides, from dendritic through skeletal to subhedral, appear to be consistent with such changes in the thermal gradient of the crust. Similar changes in the crystal habits of FeTi oxides are seen in an inflated pahoehoe sheet lobe from the Pu'u'O'o-Kupaianaha lava flow field in Hawaii (Figure 16).

5.5. Interpretative Emplacement Model

Evidence presented herein from the Roza lava suggests a common process for the emplacement of pahoehoe sheet

lobes, driven by inflation and transport of lava under an insulating crust [cf. Hon *et al.*, 1994; Self *et al.*, 1997]. A model of the formation of the three-part division of Roza sheet lobes is illustrated on Figure 21 and is briefly described below.

5.5.1. Stage 1 (several hours to days). A sheet flow unit forms as hot lava breaks out from an earlier formed lobe forming several small but rapidly advancing and inflating flow lobes (Figure 21a). Adjacent lobes coalesce to form a sheet with a continuous liquid lava core beneath a undisrupted crust. Flow inflation results from expansion of the lava core and growth of the lava crust. New lava breakouts may induce a slight drop in the internal pressure, initiating rapid nucleation and growth of bubbles, which rise to the top of the liquid core and are incorporated into the crust as vesicular zones.

5.5.2. Stage 2 (several weeks). As the crust thickens, it attains sufficient strength to retain the incoming lava (Figure 21b). Accretion of new lava to the base of the upper crust is accommodated by lava inflation. Earlier additions are removed from contact with the moving lava and eventually are cooled to temperatures of brittle behavior. This cooling initiates the formation of crustal joints that are uneven due to continuous jostling of the crust during inflation. High temperatures are maintained at the basal crust/lava core boundary by continuous flux of lava. Depending on local conditions and flow rates, the basal crust may be growing at one locality but thermally deforming at another. These two competing processes prevent the basal crust from attaining substantial thickness. Slight pressure variations in the molten core continue to drive vesiculation and formation of vesicular zones. Also, small depressions or highs on the crust-core boundary surfaces bring about localized separation of flow lines and drops in the internal pressure (see inset on Figure 21b). This pressure drop may cause separation of gas and/or vesicular segregated material from the lower boundary, which rises and is incorporated into the flowing lava. A portion is trapped by the solidifying basal crust and preserved as stretched vesicles and truncated pipe vesicles and small vesicle cylinders.

5.5.3. Stage 3 (several months). The rate of inflation in the lava declines and thickening of the lava core stops when the internal hydrostatic pressure equals the strength of the crust (Figure 21c). From here, the lava core maintains a constant thickness, and ongoing inflation is entirely due to persisting growth of the lava crust, which is supported by the tensional strength of the viscous crust [e.g., Hon *et al.*, 1994]. Degassing of the liquid lava continues as before and modification of earlier formed vesiculation features continue at the lava core/basal crust boundary.

5.5.4. Stage 4 (up to a year). In the final stages of emplacement the sheet inflates slowly (Figure 21d), and vertical cylinders form due to flow-induced degassing at the base of the liquid core. The cylinders rise until they meet the base of the lava crust, where they spread laterally to form horizontal vesicle sheets. Local irregularities or instabilities initiate formation of dome-shaped pods of highly vesicular segregated material at the surface of the sheets. As a result of bubble rise and coalescence, the pods evolve into megavesicles which are buoyant. The megavesicles attempt to rise through the viscous portion of the lava crust, forming a distinct megavesicle horizon at its base. The top part of the lava core, however, is characterized by a series of continuous horizontal vesicle sheets. Further developments may involve flow by creep of the now viscous lava core, resulting in the formation of platy joints along its upper and lower boundaries (Figure 21e). Tensional stresses exerted on the lava crust during inflation are now relaxed, and about one of three crustal joints continues to

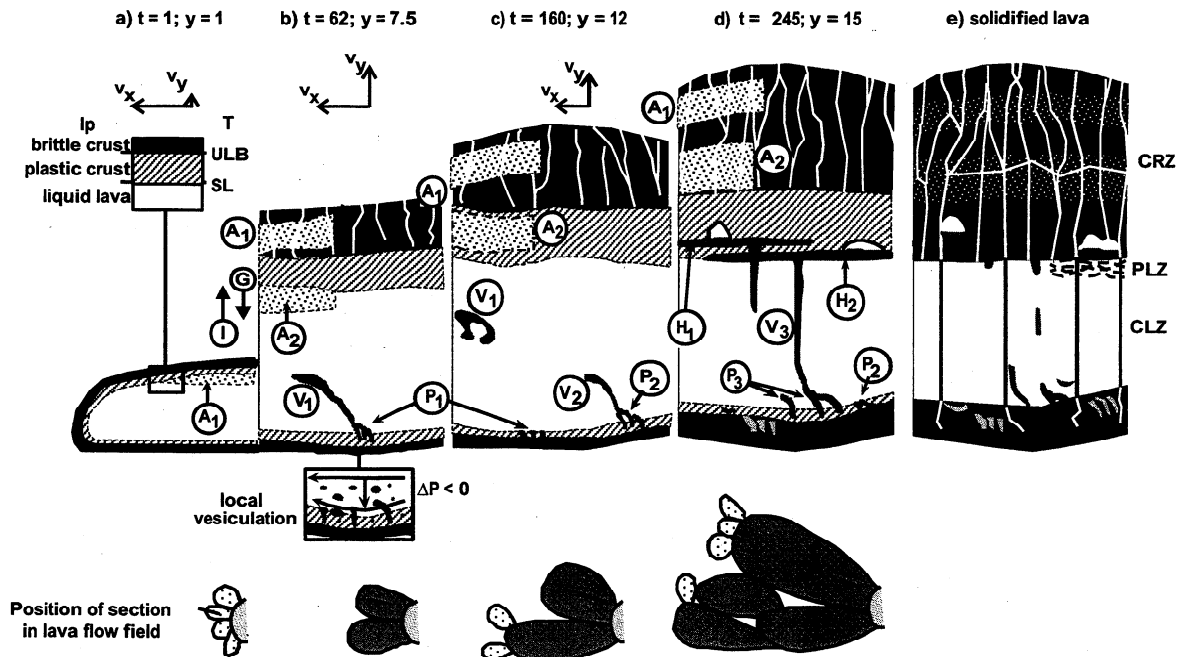


Figure 21. Idealized cross sections showing four growth stages, given in units of time (t , days) and thickness (y , meters), of a Roza sheet lobe at a fixed location: (a) Stage 1, $t = 1$, $y = 1$; (b) stage 2, $t = 62$, $y = 7.5$; (c) stage 3, $t = 160$, $y = 12$; (d) stage 4, $t = 245$, $y = 15$; (e) internal structures in solidified lava. Units of time (t) and thickness (y) are given in days and meters, respectively. Proportions of lateral and vertical expansion of flow lobe are indicated by v_x and v_y , respectively. Direction of inflation (I) and growth direction (G) of the upper lava crust are indicated by arrows. Main components are the liquid lava core (white) and the plastic (hatched) and brittle (black) portions of the crust (see key for details). Plastic crust is above temperatures of brittle behavior (ULB) but below the solidus temperature (SL) of the magma. Joints of the crustal zone (CRZ) are indicated by white lines, joints of the platy zone (PLZ) are indicated by dashed horizontal lines, and joints of the columnar zone (CLZ) are indicated by black lines. Other structural features are vesicular zones (A, dotted), pipe vesicles (P), vesicle cylinders (V), and continuous (cH) horizontal vesicle sheets. Megavesicles (white) are shown as dome-shaped features. The subscripted numbers indicate the sequence of formation of individual structures during lava emplacement. A schematic plan view of the lava flow field is given below each stage, and the location of cross section is indicated by the bar. Dark gray areas denote sheet lobes, and stippled areas denote lava breakouts from the front of an active lobe. See text for discussion.

grow as a columnar joint with further cooling, forming wide and regular columns.

5.6. Slow or Rapid Flow Emplacement?

We have shown that the concepts used previously to argue for rapid emplacement of the Roza, such as the single flow (cooling) unit criterion and the chemical subdivision of the lavas, are not consistent with the established stratigraphy or the observed lava morphology. The glassy flow margins of distal Roza lava flows do indeed record a minimum cooling of the lava during transport from vent to flow front, but they are not evidence for rapid emplacement because they can be adequately explained by insulating flow emplacement.

Furthermore, no evidence of thermal erosion has been found in the Roza lava sequence [Thordarson, 1995]. Turbulent lava flows should erode their bases by both thermal and mechanical erosion [e.g., Jarvis, 1995], and the high strain rates that develop in fast moving laminar flows will disrupt the crust and lead to production of aa (or aa-like) surfaces [Peterson and Tilling, 1980; Self et al., 1997; Keszthelyi and Self, this issue]. Thus the absence of flows with true aa lava morphologies and the absence of thermal erosion features in the Roza are inconsistent with rapid emplacement. In our view, the compound pahoehoe nature of the Roza lava flows is the most straightforward evidence against rapid lava em-

placement. It is difficult to envision how a fast moving, turbulent flow on the scale of a single Roza lava flow would break into discrete fluid elements to form a lava that consists entirely of lava lobes with dimensions that range over several orders of magnitudes.

The plagioclase phyric nature of the Roza lavas suggests subliquidus eruption temperatures and the general absence of FeTi oxides in glassy (quenched) lobe margins indicates high lava emplacement temperatures. The calculated average eruption temperature for the Roza magma is $1146 \pm 7^\circ\text{C}$ (Table 5), compatible with the experimentally determined melt temperatures of other CRBG lavas [Schiffman and Lofgren, 1982; Ho and Cashman, 1997]. Lava emplacement temperature is estimated to have been 1128°C (Table 5). These temperature estimates imply cooling rates of the order of $0.08\text{--}0.12^\circ\text{C}/\text{km}$ for the Roza lavas, values that are compatible with the suggested cooling rates of $0.02\text{--}0.04^\circ\text{C}/\text{km}$ for the Ginkgo flow of the Frenchman Springs Member [Ho and Cashman, 1997]. Low cooling rate estimates are further supported by the measured crystallinity in quenched lava selvages.

The crystal mode data indicate $\sim 20\%$ crystallization of the Roza lavas during transport and that most of the crystallization occurred at distances < 50 km from source (Figure 15). Beyond ~ 60 km from source, the degree of crystallization changed $< 10\%$ over a distance of 240 km, reflecting thermally efficient lava transport. A similar trend is found in quenched

Table 5. Estimated Eruption and Lava Emplacement Temperatures for Roza Member

Physical Property ^a	Sample	Temperature ^b , °C
Eruption	glass inclusions	1146
	s.d.	7
Temperature	whole-rock	1148
	s.d.	9
	dike margins	1148
	s.d.	4
Lava emplacement temperature	lava lobe margins	1128
	s.d.	1

^aCrystalline lava glass inclusions and quenched dike margins represent eruption temperatures, whereas lava lobe margins depict lava emplacement temperatures.

^bTemperature is calculated by MELTS [Ghiorso et al., 1997] with H₂O = 0.05 wt% and P = 1 bar and using whole rock [Martin, 1991] and groundmass glass [Thordarson, 1995] compositions of Roza eruptives.

lobe margins in the 65-km-long historic Laki lava flow in Iceland [Thordarson et al., 1996]. Furthermore, the measured sulfur content of the groundmass glass of these lava selvages from both eruptions is remarkably constant, indicating a minimal degassing, and thus temperature drop, during lava emplacement [Thordarson et al., 1996; Thordarson and Self, 1996a]. This evidence is inconsistent with rapid flow emplacement because a turbulent flow would become more rapidly crystalline and degassed with distance from source due to the much higher cooling rates [Keszthelyi and Self, this issue].

5.7. Duration of the Roza Eruption

Accepting our assertion that the Roza Member is a gigantic compound lava flow field and that its main constituents are inflated sheet lobes, we now attempt to assess its eruption duration and eruption rates. The three-part division of pahoehoe sheet lobes provides a means to estimate the emplacement duration because the boundary between lava crust and lava core boundary marks the time when the flow of fresh lava ended and the molten core became stagnant. The lava crust grows continually during emplacement, and consequently, its final thickness is a measure of the time it took to form individual lobes. In Hawaii the growth rate of the crust is proportional to rate of conductive cooling. The time it takes to form a crust H_c meter thick can be calculated by the empirical equation $t = 164.8 H_c^2$, where t is time in hours and H_c is the thickness of the upper crust in meters and 164.8 is an empirically determined constant [Hon et al., 1994]. The crust-core boundary within a sheet lobe can be positioned with reasonable accuracy, and the error of the crust thickness values given in this paper is estimated to be <10%. We assume that the above equation gives reasonable estimates for the emplacement time of individual Roza sheet lobes, but some differences in the cooling rate of Roza and Hawaiian lavas are expected because their thermal properties are likely to be slightly different.

The calculated emplacement time of 323 hours (~2 weeks) for the Kalapana sheet lobe at Kilauea volcano in Hawaii (Table 4) corresponds well with estimated duration of 2-3 weeks from direct field observations (T. Mattox, personal communication, 1997) and the results of Cashman and Kauahikaua [1997]. Similarly, the example in Table 4 from the Laki lava is situated in a compound flow field that was, according to contemporary account, formed over a period of 22 days between June 20 and July 12, 1783 [Thordarson and Self, 1993]. The calculated emplacement time of ~11 days for the Laki sheet lobe is shorter but is compatible with the evidence

from contemporary accounts because it is only one of several lobes formed in that period of time. According to our estimates the emplacement time for most Roza sheet lobes was of the order of months to couple of years, although a few indicate emplacement time of 3 to 4 years (Table 2). Despite the uncertainties in the calculations, these values clearly indicate that effusion of lava was sustained for a long time.

The Roza Member consists of two or more sheet lobes at many locations, but it is unlikely that one lobe would actively inflate underneath another active lobe. Therefore the sum of durations calculated for each lobe should give a reasonable estimate of the time required to form the Roza lava sequence at any one locality. These durations range from ~0.3 to ~4.5 years for individual localities (Table 2), further emphasizing the long duration of lava effusion and emplacement during the Roza eruption. These estimates assume that there is no time break between emplacement of successive lobes, which may be a reasonable approximation based on the evidence given in section 5.1 and that inflation of each lobe was continuous at the same rate.

The durations attained cannot simply be used to obtain an estimate of total duration of the Roza eruption as no single locality contains a record of the entire Roza eruption. Although the stratigraphic position and distribution of the four Roza lava flows (chemical subtypes I-IV) are reasonably well known the estimate is not straightforward. Each lava flow consists of multiple sheet lobes arranged in vertical and lateral associations, but the temporal relationship of horizontally arranged lobes is not known on a regional scale. Assuming that negligible time elapsed between the formation of each lava flow, a minimum estimate for the duration of the eruption can be obtained by summing the longest recorded duration for each of the four Roza lava flows (Table 6), giving a total eruption duration of ~14 years. The durations derived by using the average crust thickness for each flow (6.1 years, Table 6) are probably overly conservative, because several localities record activity that lasted for more than 4 years (Table 2). Despite uncertainties in our estimates, we feel confident in suggesting that the emplacement of the 1300 km³ Roza lava flow field took at least a decade. Assuming a duration of 14 years for the Roza eruption, the average mass eruption rates were of the order of 4.2×10^6 kg/s, which is about 3 orders of magnitude lower than previous estimates [Shaw and Swanson, 1970; Swanson et al., 1975]. This eruption rate is still very large when compared to historical eruptions and is roughly equal to the peak eruption rates of the 1783-84 Laki flood lava eruption in Iceland, the biggest lava outpouring on Earth in the last 250 years [Thordarson and Self, 1993].

Table 6. Estimated Duration of the Roza Eruption using equation (1), Based on the Averaged and Maximum Crustal Thicknesses in Roza Lava Flows

Lava Flow	Average t , years	Maximum t , years	Location of Maximum t	Other Localities
1	0.4	0.6	RSF	RAC, RBB
2	1.5	4.5	RHB	RDC, RBB, RHR, RWK, RWV
3	2.5	4.3	RMC	RSU, RFC, RBL, RBB
4	1.6	4.2	RCF	RDV, RDC, 16-C, DC-15, RSF
Total	6.1	13.6		

See Table 1 for locality key and measured thicknesses.

6. Conclusions

We have presented several lines of evidence for the compound nature of the Roza lava flow field and the origin of its component flow lobes as inflated pahoehoe lava. The morphology and structures of Roza lavas are identical to but sometimes orders of magnitude larger than those of other inflated pahoehoe lava flow fields. Also, the three-part internal structure of Roza sheet lobes is characteristic for inflated pahoehoe lava flows of all scales across the globe and is a useful criterion for identifying lava flows that grew by inflation in ancient stratigraphic sequences. Our data also suggest that a flood basalt lava flow field such as Roza can be produced by a long-lasting eruption and that this conclusion probably applies to many large, compositionally homogenous lava bodies in the CRBG and other provinces [e.g., *Self et al.*, 1997]. Inflated flows are also thought to be important in the emplacement of Archaean komatiite lava flows [Hill and Perring, 1996]. Thus inflation and insulating emplacement may be a universal process that has operated throughout Earth's history.

The lava emplacement model presented here qualitatively explains the overall morphology and structures of pahoehoe sheet lobes in Roza and other flood lavas, and when combined with the cooling model of *Hon et al.* [1994], it permits an estimate of the eruption duration. We arrive at an eruption duration of ~14 years for the Roza eruption, indicating an average mass eruption rate of 4.2×10^6 kg/s. These rates could easily be accommodated by moderate activity on relatively short segments of the ~150-km-long Roza vent system. The Roza lava flows were produced by distinct eruption episodes that may have lasted for months to years before the activity migrated to a different part of the vent system. Although our estimate of Roza eruption rate is ~3 orders of magnitude lower than previous estimates [e.g., *Swanson et al.*, 1975], an eruption like Roza would still have been of catastrophic proportions.

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T. Thordarson, CSIRO Magmatic Ore Deposit Group, Division of Exploration and Mining, Private bag P.O Box Wembley, Western Australia 6014, Australia (e-mail: t.thordarson@per.dem.csiro.au.)

S. Self, Department of Geology and Geophysics, School of Ocean and Earth Science Technology, University of Hawaii 2525 Correa Road, Honolulu, HI 96822 (e-mail: self@soest.hawaii.edu.)

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