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Chemical discrimination of Columbia River basalt flows

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[1] The homogeneity and distinctive chemical composition of individual Columbia River basalt flows are illustrated in a series of chemical plots, and the procedure for flow identification is outlined. The unique characterization of many individual eruptions permits units to be mapped from feeder dike to flow margins across the Columbia Plateau for hundreds of kilometers, and so provides critical constraints on the physical and chemical evolution of this continental flood basalt province.

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1. Introduction

[2] The Columbia River Basalt Group (CRBG) is a Miocene continental flood basalt province that covers approximately 200,000 km^2 (77,000 square miles) in southeastern Washington, northeastern Oregon, and western Idaho (Figure 1) [*Swanson et al.*, 1979; *Tolan et al.*, 1989; *Hooper*, 1997]. While of an order of magnitude smaller and younger than other classic continental flood basalt provinces (Deccan, Karoo, Parana, and Siberian Traps), it is nevertheless typical of such provinces in its rapid eruption of homogeneous tholeiitic basalt to form an extensive basalt plateau with sheet flows of great volume.

[3] The CRBG has been studied in more detail than older flood basalts because of its relatively small size, young age, arid climate, and easy accessibility. Most individual CRBG flows are difficult to identify with certainty in the field, but many flows and their feeder dikes can be distinguished in the laboratory by their chemical composition. Using chemical methods individual flows have been traced across the Columbia Plateau for hundreds of kilometers [*Tolan et al.*, 1989; *Hooper and Swanson*, 1990; *Reidel et al.*, 1992; *Hooper et al.*, 1995b; *Hooper and Gillespie*, 1996]. The flow-by-flow mapping is made possible by the remarkable homogeneity of individual eruptions, despite their huge volumes. This ability to trace the passage of individual flows and to determine their areal extent and volume provides important constraints on the physical and chemical evolution of the CRBG province which are pertinent to other, less well studied flood basalt provinces. This paper demonstrates

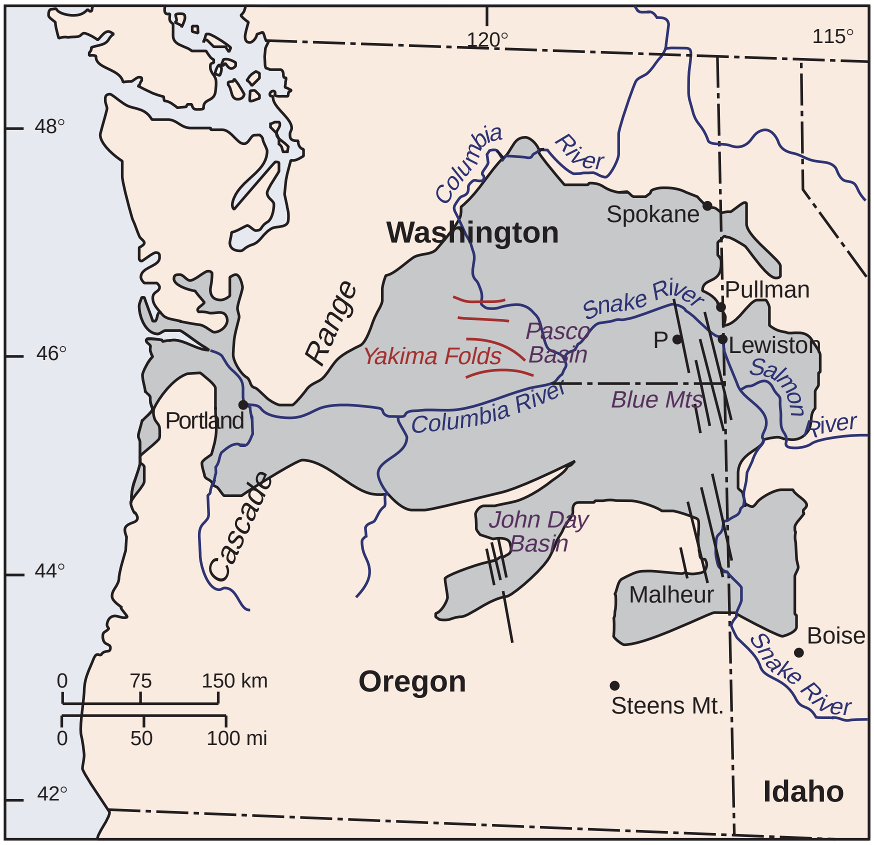

Figure 1. Areal distribution of the Columbia River Basalt Group which forms the Columbia Plateau. The map shows the main NNW-SSE feeder dike systems and the Yakima folds. Simpler east-west folds occur along the Blue Mountains to the east. The main flows erupted in the southeast quadrant of the Columbia Plateau and flowed downslope to accumulate in the evolving Pasco Basin. Larger eruptions overflowed the Pasco Basin to continue down the ancestral Columbia River valley, across the rising Cascade Range, to reach the Pacific Ocean. The John Day Basin is filled by the Picture Gorge Basalt fed from its own feeder dikes. The great majority of samples used in this study were collected in southeast Washington between Pullman and the Blue Mountains. P, Pomeroy.

the chemical homogeneity of individual CRBG flows and the subtle but consistent differences between them which allow such "chemical mapping" and discusses the importance of flow-by-flow mapping in constraining petrogenetic models.

2. Stratigraphic Nomenclature

[4] The stratigraphic sequence of Columbia River basalt flows is shown in Table 1. The essential features of the stratigraphy were formalized by *Swanson et al.* [1979]. Later alterations pertinent to mapping in southeast Washington include the identification of individual flows within the Frenchman Springs [*Beeson et al.*, 1985] and the Roza [*Martin*, 1989] Basalts. In mapping the Pomeroy sheet of southeast Washington, *Hooper and Gillespie* [1996] recognized that the Shumaker Creek flow lay above the flows of the Frenchman Springs Member and not below them as pre-

Table 1. Stratigraphic Nomenclature of the Columbia River Basalts, Southeastern Washington[a]

			Flow	
Formation	Member	Age[b], Ma	Name	Symbol
Saddle Mountains Basalt	Lower Monumental	6	Lower Monumental	Tlm[c]
			Tammany Creek	Ttm[c]
	Ice Harbor		Goose Island	Tig
			Martindale	Tim
			Basin City	Tib
	Buford		Buford	Tb
	Elephant Mountain	10.5	Elephant Mountain	Tem
			basalt of Eden	Tn[c]
	Pomona	12	Pomona	Tp[c]
			Weippe	Tweip[c]
	Esquatzel		Esquatzel	Tesq
	Weissenfels Ridge		Slippery Creek	Twt
			Tenmile Creek	Twt
			Lewiston Orchards	Twl
			Cloverland	Twc
	Asotin		Asotin	Ta
	Wilbur Creek		Wilbur Creek	Tw
	Umatilla Tu		Sillusi	Tus
			Umatilla	Tuu
Wanapum Basalt	Priest Rapids		Lola	Tprl
			Rosalia	Tprr
	Roza Tr		Roza	Tr1, Tr2
	Shumaker Creek/Powatka		Shumaker Creek	Tsh[c]
			Powatka	Tpow[c]
	Frenchman Springs	15.3	Lyons Ferry	Tfly
	(Rondowa flow, Oregon[c])		Sentinel Gap	Tfsg
			Sand Hollow	Tfsh
			Silver Falls	Tfsf
			Gingko	Tfg
			Palouse Falls	Tfpf
	Lookingglass		Lookingglass	Tlg
Eckler Mountain Basalt	Dodge		Dodge	Ted
	Robinette Mountain		Robinette Mountain	Ter
Grande Ronde Basalt	Sentinel Bluffs N2	15.6	Stember Creek	Tgsc
	N2	15.8	Field Springs	Tgfs
	R2		Meyer Ridge	Tgmr
	R2		many undesignated	Tgr2
	N1	15.8	many undesignated	Tgn1
	R1	16.5	many undesignated	Tgr1
Imnaha Basalt	No	16.5		Ti

[a] From *Swanson et al.* [1979] with modifications from *Beeson et al.* [1985], *Martin* [1989], and *Hooper et al.* [1995b]. The flow labels are used on all subsequent chemical plots.

[b] Ages from *Tolan et al.* [1989], *Baksi* [1994], and Lees et al. (submitted manuscript, 2000).

[c] Relative age unknown as flows are not in contact.

viously supposed. The Shumaker Creek flow could not therefore be included in the Eckler Mountain Member as defined by *Swanson et al.* [1979]. To accommodate this new evidence,

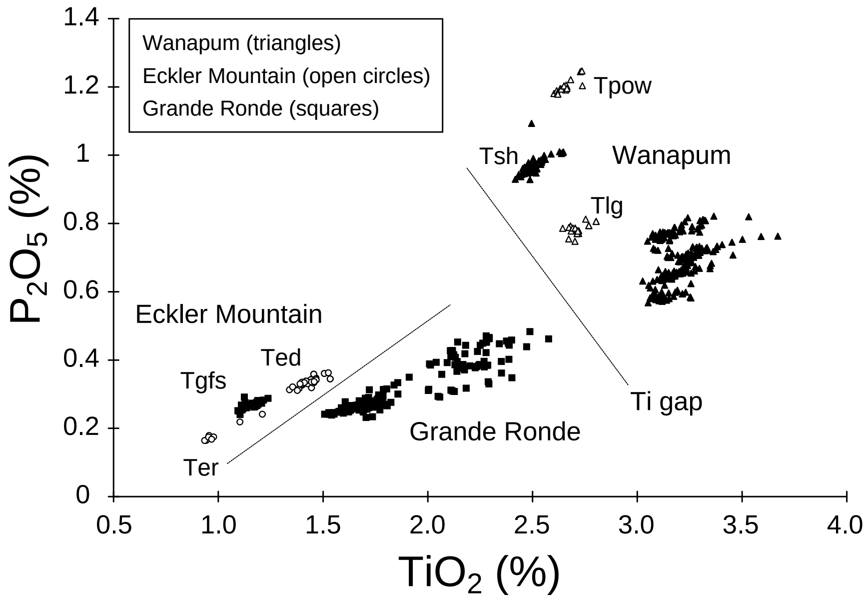

Figure 2. TiO_2 versus P_2O_5 plot of the Grande Ronde, Eckler Mountain, and Wanapum Basalts, illustrating the chemical differences between these three formations. The overlap of the Grande Ronde Field Springs flow with the Eckler Mountain Basalt is resolved in Figure 4 below. The "Ti gap" of *Seims et al.* [1974] separates all the lower formations, including the Imnaha Basalt, which is not shown, from the Wanapum Basalt. See Table 1 for flow labels. The unlabeled closed triangles represent the large flows of the Frenchman Springs, Roza, and Priest Rapids Members of the Wanapum Basalt, which have similar compositions.

Hooper et al. [1995b] informally gave the Shumaker Creek separate member status within the Wanapum Basalt Formation, leaving only the basalt of Robinette Mountain and the five recognized basalt flows of the Dodge Member within the Eckler Mountain Basalt. The distinctive chemical signature of the reduced number of Eckler Mountain Basalt flows encouraged *Hooper et al*. [1995b] to raise the Eckler Mountain Basalt to formation status as *Swanson et al*. [1979] had predicted (Table 1).

[5] The CRBG eruption started about 16.5 Ma with an outpouring of basalt at Steens Mountain in eastern Oregon above the Yellowstone hotspot [*Takahahshi et al*., 1998; *Hooper et al*., 1995a; K. R. Lees et al., Geochronology and chemical stratigraphy of Miocene to Recent volcanism in east-central Oregon, submitted to *Geological Society of America Bulletin*, 2000, hereinafter referred to as K. R. Lees et al., submitted manuscript, 2000]. Eruption then moved rapidly north to the Oregon-Washington-Idaho borders taking thousands rather than millions of years. There, deep canyons of the prebasalt topography were filled by the strongly plagioclase- and olivine-phyric Imnaha Basalt. The resulting planar basalt surface was consistently tipped in a westerly direction [*Hooper and Camp*, 1981], so that the later and even larger volumes of dominantly aphyric and evolved Grande Ronde Basalt flowed westward where it began to fill the older NNW-SSE graben that formed the evolving Pasco Basin [*Reidel*, 1983]. The Grande Ronde Basalt formed 85% by volume of the whole CRBG eruption. It was followed, after a

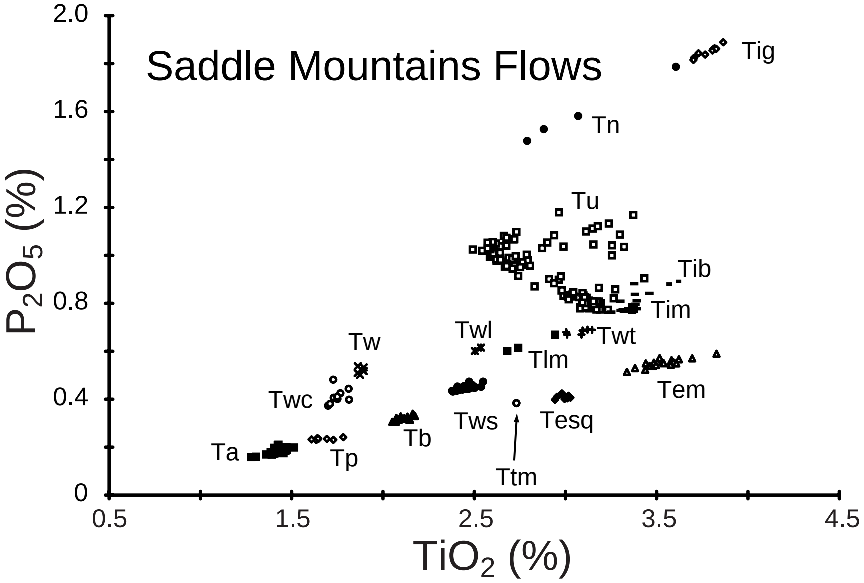

Figure 3. TiO_2 versus P_2O_5 for all Saddle Mountains flows, most of which are clearly distinguished from each other on this diagram. Overlap between the Saddle Mountains flows and those of the lower formations is considerable and is resolved in Figures 4–10. Note that the higher $^{87}Sr/^{86}Sr$ values of all Saddle Mountains Basalt flows relative to those of all the lower formations provide an ultimate discriminant. Flow labels are given in Table 1.

short hiatus, by more primitive tholeiites of the Eckler Mountain Formation and then by more Fe-rich but silica-poor tholeiites of the Wanapum Formation. Magmatism then decreased as the generally smaller and chemically diverse flows of the Saddle Mountains Basalt Formation erupted over a more protracted period from 14 to 6 Ma [*Tolan et al.*, 1989].

3. Flow Identification

[6] The chemical plots of Figures 2–10 are in the order routinely followed in identifying an unknown flow. The analyses that were used to generate the plots can be found in the appendix. All of these analyses were produced by XRF in the GeoAnalytical Laboratory of Washington State University on a fully automated Rigaku 3370 spectrometer [*Johnson et al.*, 1999]. Most of the samples were collected from the southeast part of Washington State. For those flows which are poorly represented in southeastern Washington, samples have been selected from neighboring areas farther west in central Washington (the Ice Harbor and Esquatzel Members of the Saddle Mountains Basalt; the basalts of Palouse Falls, Gingko, Silver Falls, and Sand Hollow of the Frenchman Springs Member of the Wanapum Basalt) or in adjacent Oregon and Idaho (the Powatka and Lookingglass flows of the Wanapum Formation and the Imnaha Basalt, the main sections of which occur along the northern Oregon-Idaho border [*Hooper et al.*, 1984]).

[7] Distinguishing between individual Grande Ronde flows has proved most difficult. However, even in these monotonously similar-looking aphyric flows, the precise analyses of major and trace elements, when tied to careful

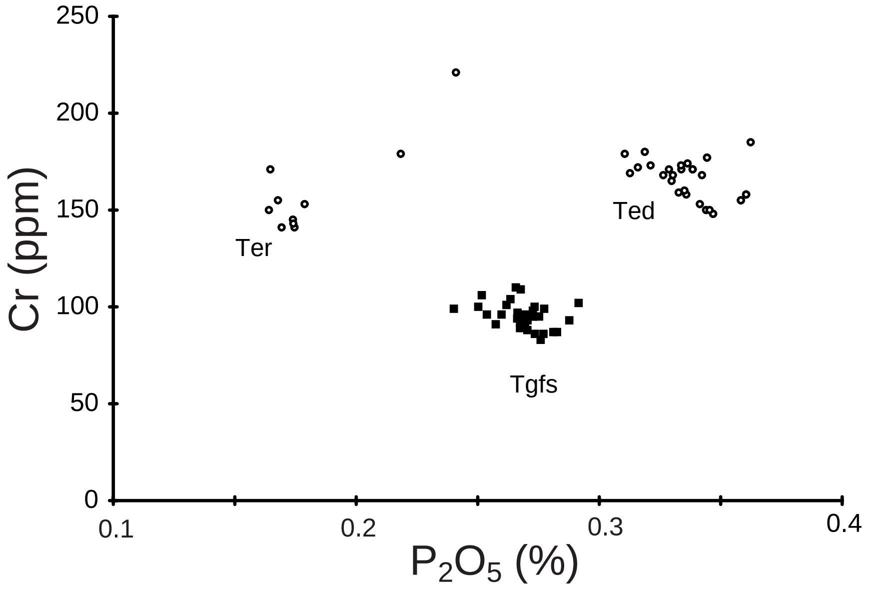

Figure 4. Cr versus P_2O_5. Cr content distinguishes the Field Springs (Grande Ronde, Tgfs) flow from flows of the Eckler Mountain Basalt (Ted and Ter).

field work and petrography, have permitted regional correlations [*Mangan et al*., 1985; *Reidel et al*., 1989]. In this report only the top three Grande Ronde flows in the Lewiston Basin area of southeast Washington have been distinguished. These are, from top down, the basalt of Stember Creek, the basalt of Field Springs, and the basalt of Meyer Ridge (Table 1). The broader, informal units identified by *Reidel et al*. [1989] in the Grande Ronde Basalt (Slack Canyon, Winter Water, Umtanum, Ortley, Armstrong Canyon, Grouse Creek, and Mount Horrible) are not distinguished; most of them are best recognized farther to the west in central Washington.

4. Procedure

[8] The TiO_2 versus P_2O_5 plot is the single most useful way of distinguishing individual flows of the Columbia River Basalt Group [*Hooper*, 1997]. Both elements are stable under the mild weathering conditions on the Columbia Plateau, and their analysis by XRF is very precise. On such plots there is overlap between flows of the Imnaha Basalt, the Grande Ronde Basalt, and the Saddle Mountains Basalt, so these three groups are first separated by other means. The Imnaha, at the base of the succession, is clearly distinguished in the field by its porphyritic mineralogy and by its lower silica and potassium contents. The Imnaha Basalt is poorly represented in southeast Washington. Recognition of individual flows is discussed by *Hooper et al*. [1984] and is not considered further here. Saddle Mountains flows, at the top of the succession, are distinguished by their higher $^{87}Sr/^{86}Sr$ ratios [*Hooper*, 1984] and lower Sr contents (see below, Figure 6); Saddle Mountains flows can also be distinguished from earlier flows (Grande Ronde, Eckler Mountain, and Wanapum) by the use of other chemical plots, as seen below.

[9] Two P_2O_5 versus TiO_2 plots are used. First, Figure 2 emphasizes the major differences between the Grande Ronde, Eckler Mountain, and Wanapum Basalt Formations.

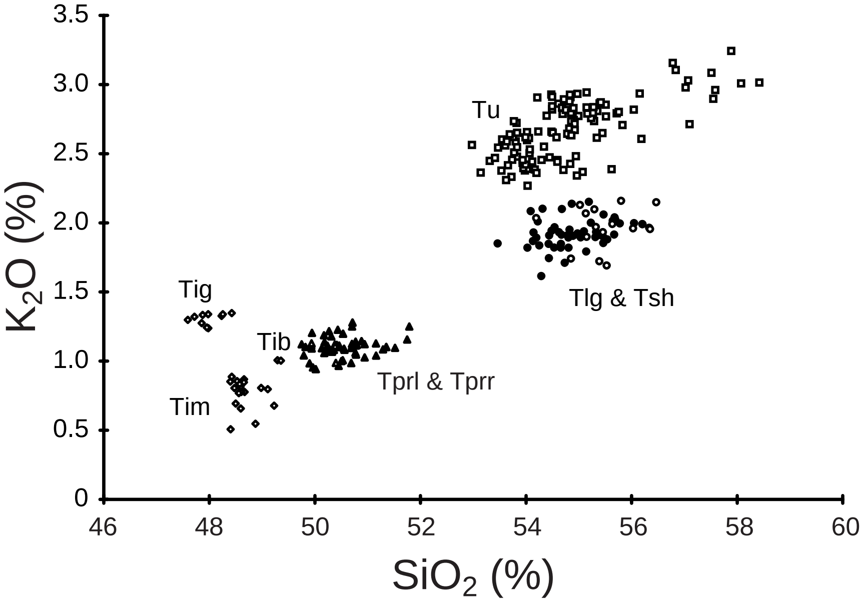

Figure 5. K_2O versus SiO_2. All three Ice Harbor Dam flows (Tig, Goose Island; Tib, Basin City; Tim, Martindale) and the two flows of the Priest Rapids Member (Tprl, Lolo; Tprr, Rosalia) are clearly distinguished from the flows of the Umatilla Member (Tu). K_2O is also seen as a useful discriminant (as is Ba) between the Umatilla Member of the Saddle Mountains Basalt and the Lookingglass (Tlg) and Shumaker Creek (Tsh) Members of the Wanapum Basalt.

The “Ti gap” between the Wanapum Basalt and the older formations [*Seims et al.*, 1974] has long proved a useful marker horizon in correlating borehole samples from the central Columbia Plateau. The large chemical differences between the Eckler Mountain Basalt and the immediately overlying basalt of Lookingglass (Tlg) across the Ti gap suggests placing the Lookingglass flow at the base of the Wanapum rather than at the top of the Eckler Mountain Basalt (Table 1).

[10] The second P_2O_5 versus TiO_2 plot (Figure 3) illustrates how this plot can distinguish almost every flow of the Saddle Mountains Basalt. Thus phosphorus versus titanium plots (Figures 2 and 3), in addition to usefully separating some of the major formations of the CRBG, allow precise identification of the following flows: the Lookingglass (Tlg), Shumaker Creek (Tsh), and Powatka (Tpow) flows of the Wanapum Basalt and the Goose Island (Tig), Eden (Tn), Elephant Mountain (Tem), Wilbur Creek (Tw), Asotin (Ta), Cloverland (Twc), Lewiston Orchards (Twl), Esquatzel (Tesq), Lower Monumental (Tlm), and Tammany Creek (Ttm) flows of the Saddle Mountains Basalt. These distinctions can be confirmed in most cases by other chemical plots.

[11] In particular cases where overlap or less than complete separation between flows occurs on P_2O_5 versus TiO_2 plots, the flows can be resolved on other chemical plots. For example, the Cr versus P_2O_5 plot (Figure 4) distinguishes the Robinette Mountain (Ter) and the various Dodge flows (Ted) of the Eckler Mountain Basalt from the Field Springs flow (Tgfs) of the Grande Ronde Basalt, which overlap in Figure 2. The SiO_2 versus K_2O plot (Figure 5) separates all three Ice Harbor flows (Goose Island, Tig; Basin City,

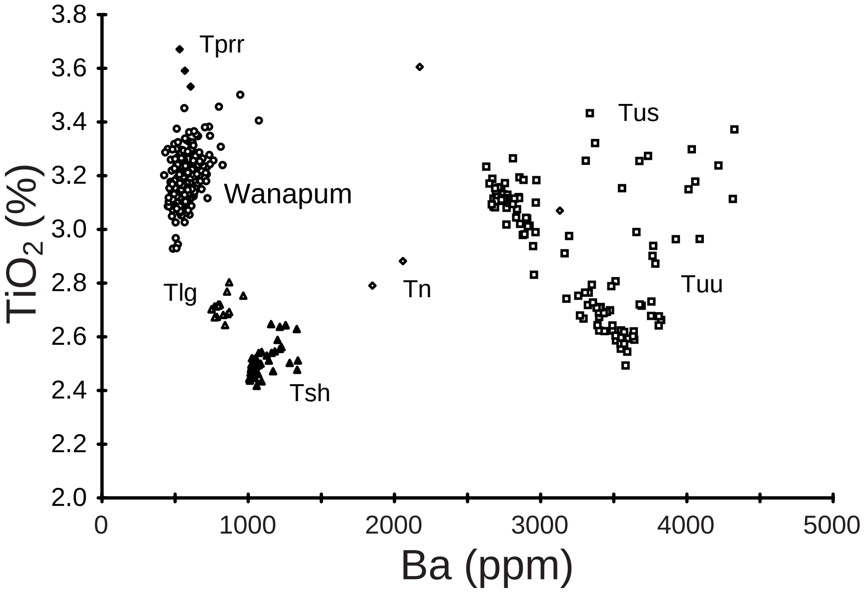

Figure 6. TiO_2 versus Ba plot. The very high Ba content (>2500 ppm) defines the two flows of the Umatilla Member and, with TiO_2, distinguishes two separate eruptions from the same vent: the Umatilla (Tuu) and Sillusi (Tus). The gradation between the two flows suggests mixing during eruption, while the scatter from both eruptions toward more evolved compositions with higher Ba and TiO_2 values is restricted to the vent areas in the Lewiston Basin. High Ba content (>1000 ppm Ba) can also be used to identify the Eden (Tn) and Shumaker Creek (Tsh) flows. The Eden flow (Tn) shows a similar scatter toward more evolved compositions in samples from close to the vents. Tprr, Rosalia (Priest Rapids Member of Wanapum); Tlg, Lookingglass; Tsh, Shumaker Creek. The large Wanapum group includes the Lolo flow of the Priest Rapids Member and flows of the Roza and Frenchman Springs Basalt Members.

Tib; and Martindale, Tim flows) from the more siliceous Umatilla flows (Tu) and from the two flows of the Priest Rapids Member (Lolo, Tprl; Rosalia, Tprr) all of which display some overlap on phosphorus-titanium plots. Potassium content (Figure 5) also separates the Umatilla flows from the Lookingglass (Tlg) and Shumaker Creek (Tsh) flows more clearly than do Figures 2 and 3.

[12] The Umatilla Member can be identified by uniquely high but variable Ba content (Figure 6). The Umatilla Member has an unusually wide range of compositions and is interpreted here as two sequential eruptions, the Umatilla flow (Tuu) and the Sillusi flow (Tus), erupted from the same vent and partly mixed just prior to eruption. Small volumes of similar but even more evolved basalt (higher Ba and TiO_2) occur locally around the vent and feeder dike area on the southern edge of the Lewiston Basin, Washington. Higher than normal Ba content (>1000 ppm Ba) can also be used to identify the Eden (Tn) and Shumaker Creek (Tsh) flows of the Saddle Mountains and Wanapum Formations respectively (Table 1).

[13] The lower Sr content of many of the Saddle Mountains flows (Figure 7) can, like their higher $^{87}Sr/^{86}Sr$ ratio, be used to separate them from Grande Ronde Basalt flows with which they overlap on phosphorous-titanium plots. Thus the Pomona (Tp) and Buford (Tb) flows are distinguished from the Grande Ronde, as are the Esquatzel (Tesq) and the Tenmile Creek (Twt) flows.

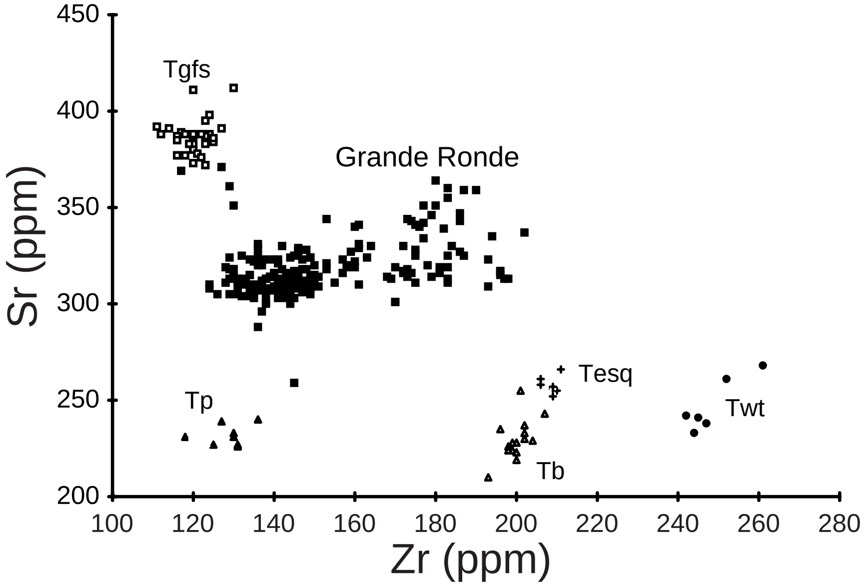

Figure 7. Sr versus Zr plot. This plot separates many Saddle Mountains flows with lower Sr and higher Zr from the Grande Ronde. The Pomona (Tp), Buford (Tb), Esquatzel (Tesq), and Tenmile Creek flows are all separated from the Grande Ronde Basalt on this plot.

[14] The SiO_2 versus P_2O_5 Plot (Figure 7) usefully separates all four flows of the Weissenfels Ridge Member (Slippery Creek, Tws; Tenmile Creek, Twt; Lewiston Orchards, Twl; Cloverland, Twc) from each other and from the Grande Ronde Basalt.

[15] The many large flows of Wanapum Basalt that make up the Frenchman Springs, Roza, and Priest Rapids Basalt Members have similar compositions and are difficult to separate clearly on chemical composition alone. Fortunately, their phenocryst and weathering characteristics often make these flows relatively easy to distinguish in the field, at least over short distances [*Beeson et al.*, 1985]. The higher P_2O_5 content of both Priest Rapids flows helps to distinguish this member from flows of the Frenchman Springs and Roza Members, and the much higher Cr content of the Lolo flow (Tprl) separates it from the Rosalia flow (Tprr) (Figure 9). Finally, the Cr content can be used to discriminate the top three flows of the Grande Ronde basalt present in southeast Washington (Figure 10).

5. Discussion

[16] The ability to identify flows of the Columbia River Basalt Group by their chemical composition is due to the remarkable homogeneity of the basalt reaching the surface in a single flood basalt eruption. The huge volumes of evolved yet homogeneous tholeiitic magma were erupted from deep fissure systems in a very short time, characteristics common to all true flood basalt provinces (e.g., the Deccan [*Beane et al.*, 1986; *Thorat and Subbarao*, 1996]) and differ from eruptions in other types of igneous provinces such as oceanic hotspots (Hawaii, Galapágos, or Iceland) or eruptions associated with plate margins. The homogeneity of individual CRBG eruptions, and known to occur for at least some flows in the Deccan and Karoo provinces, suggests that a better understanding of the older and larger flood

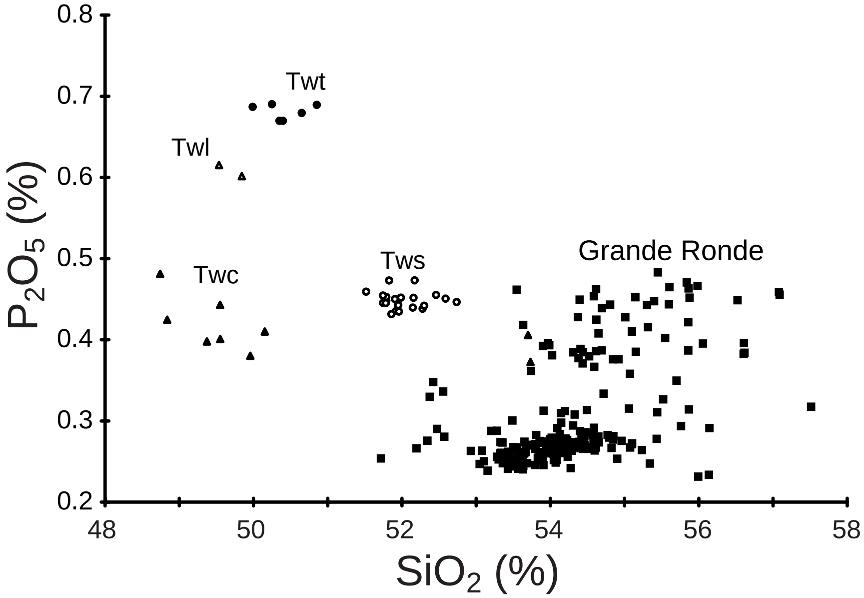

Figure 8. P_2O_5 versus SiO_2. This plot distinguishes all four flows of the Weissenfels Ridge Member from each other and from the Grande Ronde Basalt. Twt, Tenmile Creek; Twl, Lewiston Orchards; Twc, Cloverland; Tws, Slippery Creek flows. Note that two samples of Twc have significantly higher SiO_2 values and fall within the Grande Ronde field, while similar to other Twc samples in stratigraphic position and composition (Figure 3). One sample, at least, was collected immediately adjacent to sediment, and some local contamination may have caused the discrepancy.

basalt provinces will result from a similarly detailed field and chemical mapping program. The resulting flow-by-flow characterization of a flood basalt province provides the necessary geochemical framework for proper petrogenetic modeling.

[17] Why and how such large volumes of evolved but homogeneous magma are produced remains one of the most difficult questions in flood basalt petrogenesis. The uniform composition of these massive outbursts of magma may be due to a combination of crystal fractionation and crustal contamination associated with particularly efficient convection systems in huge magma reservoirs in the crust [*Griselin et al.*, 1997], in which case one must ask why other magmatic systems, also ascribed to crystal fractionation, display so much more compositional variation. Alternatively, these large-volume magmas could be primary melts from an unusually iron-enriched mantle derived from a deep mantle plume with a significant component of subducted basaltic crust [*Wright et al.*, 1989; *Cordery et al.*, 1997; *Hooper*, 1997; *Takahahshi et al.*, 1998].

[18] The ability to recognize the feeder dikes and to plot the areal extent and volume of many individual flows leads to an unusually complete three dimensional view of the Columbia River flood basalt eruptions. In addition, defining the flow boundaries [*Hooper and Swanson*, 1990; *Hooper et al.*, 1995b] has allowed tracking of the contemporaneous deformation of the CRBG flows across the Columbia Plateau by determining which flows were displaced and which were not displaced by a particular structure. From this it can be shown that the E-W Yakima folds (Figure 1) were growing during

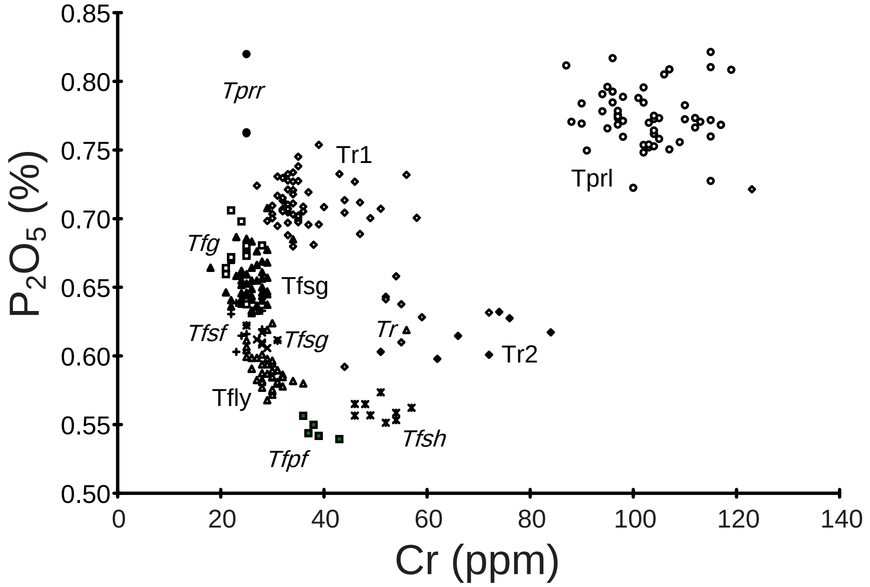

Figure 9. P_2O_5 versus Cr. The many large flows of Wanapum Basalt that make up the Frenchman Springs, Roza, and Priest Rapids Basalt Members have similar compositions and are difficult to separate clearly on chemical composition alone. The two Priest Rapids flows (Tprr, Rosalia; Tprl, Lolo) are distinguished by their higher P_2O_5 content, and the Lolo flow is distinguished from all the rest, including the Rosalia, by its higher Cr content. Samples from the two Frenchman Springs flows (Lyons Ferry, Tfly; Sentinel Gap, Tfsg) and two Roza flows mapped in southeast Washington can be separated by their P_2O_5 content. However, the addition of samples from other Frenchman Springs flows from the Pasco Basin (in italics) makes these distinctions less convincing over larger distances. Most of these flows can be recognized by their phenocryst mineralogy [e.g., *Swanson et al.*, 1979; *Beeson et al.*, 1985].

most of the 10 million years of the CRBG eruptions [*Reidel*, 1984]; that the E-W Blue Mountains anticline along the Oregon-Washington border (Figure 1) formed in a more limited period during the eruptions of the Eckler Mountain and early part of the Wanapum Basalt Formations [*Hooper et al.*, 1995b]; and that the Pasco Basin was sinking while the mountains of Idaho were rising, so tilting the Columbia Plateau, from well before until well after the CRBG eruptions (Figure 1) [*Hooper and Camp*, 1981]. All these structures, to which the highly oriented NNW-SSE feeder dike system and NNE-SSW left-lateral and WNW-ESE right-lateral tear faults may be added, are related to east-west extension and oblique subduction beneath the North American plate throughout the second half of the Tertiary [*Hooper and Conrey*, 1989; *Hooper et al.*, 1995b, 2000). The precise areal distribution of flows also provides the basis for charting the changing morphology of the region, helping to define the evolution of the drainage system over the last 20 million years.

[19] The huge volume and spread of individual eruptions is well illustrated by the Pomona flow, which shows no significant chemical variation from near its source to its termination. Such homogeneity throughout an eruption provides significant constraints on physical modeling of fissure eruptions which must be rapid enough to prevent any recognizable crystal settling and resulting fractionation from occurring during the eruption [*Shaw and Swanson*, 1970; *Self et al.*, 1997].

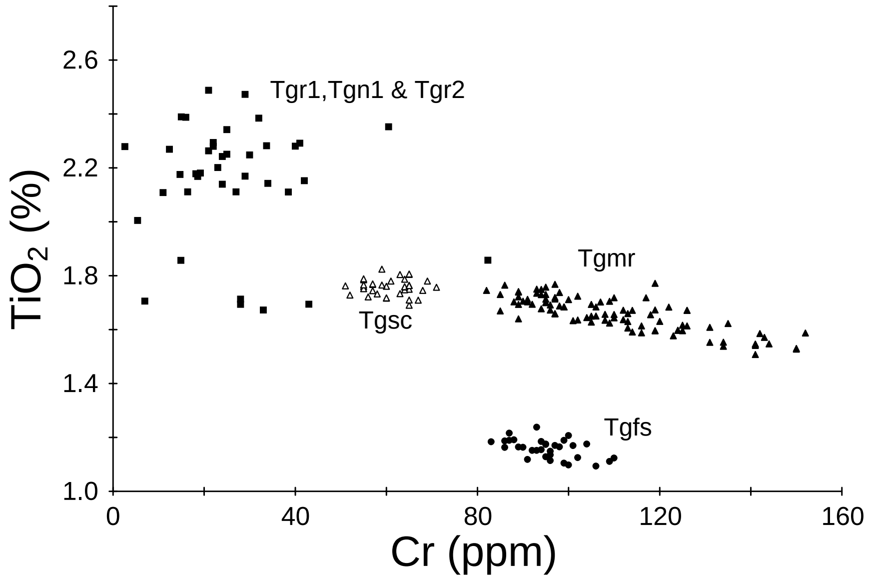

Figure 10. TiO$_2$ versus Cr. This plot distinguishes the three high-Mg flows from the top of the Grande Ronde sequence east of Pomeroy in southeast Washington (Tgsc, Stember Ridge; Tgfs, Field Springs; Tgmr, Meyer Ridge) from each other and from the low-Mg Grande Ronde flows characteristic of the Tgr1, Tgn1, and Tgr2 paleomagnetic episodes.

[20] The Pomona flow has been traced for 600 km across the Columbia Plateau from western Idaho to the Pacific Ocean [*Magill et al.*, 1982; *Hooper*, 1988, 1996]. On reaching the Pacific the Pomona lava plunged into soft offshore sediments to form a plexus of invasive sills and dikes [*Neim et al.*, 1994]. This is the longest lava flow documented so far on Earth, although it may prove to be dwarfed by flows in the larger flood basalt provinces when these have been mapped [e.g., *Baksi*, 1994].

[21] Nevertheless, caution is needed in assuming that two flow exposures of similar composition and age from different parts of a flood basalt province are part of a single eruption. Two particularly well known flows, the Dodge and the Pomona (Table 1), provide cautionary tales.

[22] The Dodge Member includes a series of mainly small flows, each chemically distinct and with its own feeder dike(s), that cross the Blue Mountains anticline along the eastern end of the Washington-Oregon border (Appendix A) [*Hooper et al.*, 1995b]. The largest of these Dodge flows is chemically indistinguishable from another flow of similar age, with its own feeder dikes, which crops out 130 km NE in northern Idaho. It is clear from the geography and lack of significant erosion that these two chemically identical flows were never connected on the surface and could not have been derived from the same eruption or even from the same NNW-SSE fissure system. We must conclude that two chemically identical flows erupted at about the same time from widely separated fissure systems.

[23] In another example the Weippe flow and associated dikes, mapped by V. E. Camp well up the Clearwater valley in central Idaho, proved to have the same chemical composition

Appendix A (Representative Sample). Columbia River Basalt Group[a] [The full Appendix A is available in ASCII tab-delimited format at http://www.g-cubed.org.]

Sample	Symbol	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Sc	V	Cr	Ni	Cu	Zn	Ga
Std GSP1	WSUXRF	68.29	0.666	15.31	3.85	0.037	1.09	2.01	2.9	5.55	0.286	4	54	16	16	31	103	23
GSP1 N=98	StDev	0.09	0.004	0.07	0.01	0.001	0.1	0.01	0.05	0.07	0.002	2	5	2	1	2	2	1
GSP1	GOV 1994	68.25	0.66	15.33	3.92	0.041	0.97	2.1	2.84	5.59	0.284	6	53	13	9	33	104	23
SADDLE MOUNTAINS BASALT																		
Lower Monumental Member																		
CA044	Tlm	51.26	2.682	13.94	12.84	0.215	5.43	9.10	2.89	1.05	0.601	37	347	76	29	17	124	27
CA056	Tlm	51.09	2.742	13.79	13.24	0.214	5.27	9.11	2.83	1.10	0.614	39	352	72	25	16	119	22
HAS025	Tlm	51.48	2.943	14.03	13.17	0.213	4.40	8.81	2.79	1.50	0.669	28	320	25	17	7	130	23
basalt of Tammany Creek																		
HAS064	Ttm	54.23	2.732	13.51	12.72	0.191	3.89	7.79	2.76	1.80	0.383	26	336	29	9	20	114	22
basalt of Eden[b]																		
PH7910	Tn	52.3	2.79	13.03	13.82	0.24	3.6	7.53	2.88	2.34	1.48	30	150	42	5	17	156	24
PH7911	Tn	53.11	2.88	13.5	12.93	0.209	2.95	7.68	2.88	2.35	1.53	31	158	39	4	20	160	20
PH78217	Tn	54.37	3.07	14.45	12	0.129	2.01	7.33	3.08	1.98	1.58	35	133	45	11	23	156	23
Ice Harbor Member																		
basalt of Goose Island																		
KJ86029	Tig	47.85	3.809	11.83	16.99	0.280	4.32	9.06	2.71	1.28	1.859	43	207	29	8	4	222	25
KJ86030	Tig	47.98	3.703	11.54	17.69	0.288	4.18	8.76	2.70	1.34	1.824	41	210	32	13	8	224	27
KJ86032	Tig	48.23	3.864	11.86	16.66	0.269	4.14	9.08	2.68	1.33	1.889	39	224	33	14	8	229	27
KJ86035	Tig	48.26	3.729	11.59	17.31	0.282	4.05	8.89	2.72	1.34	1.843	43	206	31	4	4	222	24
KJ86041	Tig	47.98	3.817	11.78	17.21	0.266	4.26	8.99	2.62	1.24	1.864	38	217	35	9	6	221	27
KJ86043	Tig	47.87	3.814	11.68	17.22	0.284	4.27	8.95	2.71	1.33	1.861	39	232	29	12	5	227	25
KJ86045	Tig	47.72	3.806	11.71	17.26	0.307	4.32	9.00	2.70	1.32	1.854	39	215	32	3	7	222	26
KJ86047	Tig	47.59	3.826	11.65	17.50	0.283	4.36	8.92	2.69	1.30	1.862	43	219	39	4	7	219	28
KJ86048	Tig	48.42	3.701	11.67	17.31	0.266	4.15	8.48	2.83	1.35	1.816	42	193	32	4	4	220	26
KJ86049	Tig	47.95	3.766	11.72	17.26	0.285	4.25	8.96	2.73	1.24	1.838	43	214	33	3	7	219	27
basalt of Martindale																		
KJ86001	Tim	48.40	3.376	13.35	14.28	0.211	6.07	10.42	2.62	0.51	0.767	44	360	181	33	37	147	25
KJ86003	Tim	48.50	3.390	13.07	14.71	0.215	5.81	10.18	2.64	0.69	0.811	40	356	171	26	34	150	20
KJ86004	Tim	48.67	3.380	13.08	14.54	0.221	5.84	10.06	2.58	0.78	0.837	42	350	163	32	35	158	24
KJ86007	Tim	48.57	3.301	13.10	14.76	0.228	5.82	9.99	2.57	0.84	0.808	43	347	174	30	30	152	22
KJ86012	Tim	48.59	3.349	13.21	14.24	0.222	6.03	10.30	2.62	0.66	0.776	40	358	176	25	32	149	23

[a] Analyses are by XRF in the GeoAnalytical Laboratory, Geology Department, Washington State University, Pullman, WA 99164. Analyses are normalized on a volatile-free basis, with total iron reported as FeO [*Johnson et al.,* 1999]. Samples marked with an asterisk are from the Grande Ronde Basalt type section [*Camp et al.,* 1978].

[b] Stratigraphic position uncertain.

as the Pomona flow (Appendix A), the nearest exposure of which occurs in the Lewiston basin, some 60 km to the west on the Washington-Idaho border. It was tentatively assumed that the Weippe represented the feeder dikes to the Pomona flow, despite their geographic separation. Subsequent work on magnetic orientation, however, showed significant discrepancies between the Pomona and the Weippe units which seemed unlikely to be explained by subsequent tectonism. Proof that these two flows represent two distinct eruptions, albeit of similar chemical composition and age, has now been confirmed by their different isotopic signatures (Appendix A, Eckler Mountain and Wanapum Basalts, CRBG).

[24] Similar problems have arisen in the Deccan province [*Peng and Mahoney*, 1995; *Peng et al*., 1998] and are one of the main barriers to developing a full understanding of the evolution of that large province. Some flows in the Narmada valley in the north of the Deccan have similar chemical compositions to those along the western Ghats to the south. In some cases these are in different stratigraphic order. In other cases, flows from the north and the south have different magnetic and/or isotopic signatures [*Sreenivasa Rao et al*., 1985; *Peng and Mahoney*, 1995; *Mahoney et al*., 2000]. Clearly flows of similar composition can be erupted at different times and at about the same time but far apart and from different feeder systems. Chemical similarity alone does not prove that two widely separated basalt flows in a flood basalt province are from the same eruptive event. To gain a full understanding of flow stratigraphy in flood basalt provinces, flows must be carefully traced in the field.

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