The Origin of the Columbia River Flood Basalt Province: Plume versus Nonplume Models

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ABSTRACT

As a contribution to the plume-nonplume debate we review the tectonic setting in which huge volumes of monotonous tholeiite of the Columbia River flood basalt province of the Pacific Northwest, USA, were erupted. We record the time-scale and the locations of these eruptions, estimates of individual eruption volumes, and discuss the mechanisms of sheet-flow emplacement, all of which bear on the ultimate origin of the province. An exceptionally large chemical and isotopic data base is used to identify the various mantle sources of the basalt and their subsequent evolution in large lower crustal magma chambers. We conclude by discussing the available data in light of the various deep mantle plume and shallow mantle models recently advocated for the origin of this flood basalt province and we argue that the mantle plume model best explains such an exceptionally large volume of tholeiitic basalt erupted over an unusually short period and within such a restricted area.

INTRODUCTION

Advocates of mantle plumes have long considered continental flood basalt provinces to be one of the most obvious expressions of plume activity (Campbell and Griffiths, 1990; Richards et al., 1989). As the youngest (Miocene) and smallest of the classic continental flood basalt provinces, the Columbia River province of the American Northwest (Fig. 1) is particularly appropriate for pursuit of the plume versus nonplume debate. It is the most fully exposed and least altered of these provinces and its easy accessibility has led to comprehensive studies, culminating in a detailed knowledge of the flow stratigraphy (Fig. 2) and in the accumulation of an exceptionally large amount of physical, chemical and isotopic data bearing on its ultimate origin.

The Columbia River Basalt Group (CRBG) forms a high plateau of stacked sheet-flows between the Cascade Range to the west and the Rocky Mountains to the east. It covers large areas of southeast Washington State, northeast Oregon and adjacent parts of western Idaho (Fig. 1). The voluminous tholeiitic basalt eruptions began about 16.6 Ma in and around Steens Mountain in east-central Oregon; (Swisher et al., 1990; Hooper et al., 2002a; Camp et al., 2003). The main focus of the eruptions then moved progressively north along the NNW oriented Chief Joseph dike swarm on the eastern borders of Oregon and Washington (Fig. 1) so that, by 6 Ma, the youngest flows were erupting in southeast and central Washington.

Some fissure-dike systems are over 100 km long, feeding homogeneous basaltic sheet-flows that were tens of meters thick and thousands of cubic meters in volume (Tolan et al., 1989; Reidel et al., 1989). Numerous flows have been correlated with their feeder dikes and traced over the Columbia Plateau by their remarkably constant and distinct chemical compositions (Fig. 3; Hooper, 2000). Individual flows crossed the Plateau from the feeder dikes on the eastern edge of the province to the Cascade Range, ponding in the Pasco Basin on the way. Larger flows continued down the path of the ancestral Columbia River across the rising Cascade arch to the Pacific Ocean, a journey of over 600 kilometres. The east-to-west transport was facilitated by an evolving east-to-west slope (1^o to 2^o) resulting from both the continued rise of the region to the east along the Idaho-Oregon border and the continued deepening of the Pasco Basin in the central Plateau. Recent estimates suggest that an area greater than 200,000 km^2 was covered by 234,000 km^3 of basalt (Camp et al., 2003). Over 98% of this huge volume of basalt erupted in the first two million years (16.6 Ma to14.5 Ma; Waters, 1961; Swanson et al., 1979; Tolan et al., 1989; Hooper et al., 2002a).

Most workers with direct experience of the CRBG and associated magmatism have followed Brandon and Goles (1988) and embraced the plume model for the origin of the CRBG (Draper, 1991; Pierce and Morgan, 1992; Hooper and Hawkesworth, 1993; Takahahshi et al., 1998; Hooper et al., 2002a; Camp and Ross, 2004). But alternative, nonplume models have also been proposed (Carlson and Hart, 1987; Smith, 1992; King and Anderson, 1998; Humphreys et al., 2000; Christiansen et al., 2002; Hales et al., 2005). This contribution reviews the abundant physical, chemical and isotopic data available for the Columbia River province and discusses the extent to which this data supports either the mantle-plume or the alternative shallow mantle models.

TECTONIC SETTING OF THE CRBG ERUPTION

The CRBG was erupted in the intermontane zone between the Cascade Range and the Rocky Mountains. The basalts were extruded in huge volumes primarily through the feeder dikes of the Chief Joseph dike swarm, which parallels the edge of the North American craton within the relatively thin lithosphere of the accreted oceanic Blue Mountains terranes (Fig. 1). The large volumes, brief period, and the restricted area of the tholeiitic flood basalt eruptions contrast with the more prolonged, partly contemporaneous but much smaller, calc-alkalic to alkalic eruptions localized along north-south grabens resulting from east-west extension (Fig. 4).

The boundary between the North American craton and the accreted terranes is marked by a complex suture zone which traces an erratic pattern across the intermontane zone. Running north from southeastern Oregon along the western edge of the Idaho batholith, it parallels the mid-Cretaceous subduction zone (Armstrong et al., 1977; Fleck and Criss, 1985), which has subsequently been foreshortened and sheared by late Cretaceous dextral transpression (Giorgis et al., 2005). Then, swinging abruptly through ninety degrees, it continues from east to west along the northern margin of the accreted terranes beneath the Columbia River basalts on the north side of the Lewiston Basin, tracked by its geophysical signature (Fig. 1; Mohl and Thiessen, 1995). Farther west the suture again runs north-south to form the eastern margin of the Pasco Basin (Fig. 1; Reidel, 1984; Sobczyk, 1994).

The Cretaceous subduction was responsible for the formation of the Idaho batholith, the rise of the Rocky Mountains (in part), and the accretion of the oceanic island arc terranes from the west. When blocked by the accreted terranes at the end of the Cretaceous, subduction jumped to the western margin of the accreted terranes, to initiate the Cascade volcanic arc in the Eocene. The North American craton, intruded by the Idaho batholith, is presumably significantly thicker and more competent than the compilation of oceanic island arcs and associated sediments welded together by Jurassic and Cretaceous granitoids which make up the accreted terranes (Vallier and Brooks, 1987, 1995).

Where the basalts flowed northwards from the Chief Joseph feeder dikes onto the craton of eastern Washington they remain essentially flat-lying. Immediately south of the cratonic margin, however, where the same flows lie on the accreted terranes, the flows are deformed into east-west folds that parallel the cratonic margin along the Washington-Oregon border from Lewiston to the Yakima Fold Belt (Fig. 1). The east-west folds include the Blue Mountains anticline and adjacent Lewiston Basin and Troy Basin synclines (Ross, 1980; Hooper et al., 1995b) in addition to the "Lewiston structure", a steep anticline broken by a high angle reverse fault in which flows dip up to 80^{o} against the cratonic margin. This deformation culminates to the west at the 'nose' of the craton (Fig. 1) with the formation of the more complex Yakima Fold Belt.

The Yakima Fold Belt straddles the Pasco Basin (Fig. 1), an actively subsiding basin where up to 20 km of Tertiary, including Eocene, sediment has accumulated. The sediment is topped by 4-5 km of ponded flood basalts. Using the thinning of individual flows over the anticlines, Reidel has shown that the Yakima folds formed during the CRBG eruptions while the Pasco Basin was actively subsiding (Reidel, 1984; Reidel et al., 1994). Similar evidence from the southwestern extension of the Yakima folds (Anderson, 1987) and the folds along the Washington-Oregon border (Ross, 1980) demonstrate that these structures grew during the CRBG eruptions, and continued later at a reduced rate (Reidel, 1984). The folds appear to result from north-south compression of the accreted terranes against the cratonic margin. This suggests that the northward component of the late-Cretaceous transpression documented by Giorgis et al. (2005) continued through the period of the flood basalt eruptions. The same north-south compressional strain remains detectable on the Plateau today (Kim et al. 1986). Further evidence of the northward translation of the accreted terranes after the basalts erupted is seen in north-south vertical breccia zones with conspicuous horizontal slickensides which cut basalt flows in the Clearwater Embayment

(PRH, unpub. data), and in right-lateral displacement farther south along vertical north-south faults that cross the Western Snake River Plain (Fig. 5a; Mabey, 1984; Ferns et al., 1993; and Hooper et al., 2002b). Given the probable 100 km shortening of the subduction zone along the western margin of the Idaho batholith, into which the accreted terranes have been wedged, as proposed by Giorgis et al (2005), the continued northward thrusting of the accreted terranes may have been the cause of the extraordinary east-west digression of the cratonic margin across southeast Washington (Fig. 1).

East-west extension has been a feature of the intermontane zone from British Columbia (Thorkelson, 1989; Breitsprecher et al., 2003) to Nevada (Fitton et al., 1988; Hawkesworth et al., 1995) since the Eocene. In northeast Washington the N-S oriented Republic and affiliated grabens of Eocene age are accompanied by calc-alkalic to alkalic magmatism (Holder et al., 1990; Hooper et al., 1995a; Morris and Hooper, 1997) while metamorphic core complexes caused by east-west extension and lithospheric thinning developed in northern and southern Idaho (Coney, 1987). Local alkalic volcanicity in west-central Idaho suggests that similar tectonic-magmatic activity, including east-west extension, may have continued through the Oligocene (Kauffman et al., 2003).

In the Miocene the northern limit of obvious Basin and Range east-west extension was the northern edge of the Blue Mountains accreted terranes and farther east across western Idaho. Extensional features are minimal in the narrow zone forming the northern edge of the accreted terranes between the east-west trending cratonic boundary in southeast Washington and the Olympic-Wallowa lineament (OWL; Fig. 1; Taubeneck, 1970). Extension becomes more obvious immediately south of the OWL with the development of the La Grande and Baker grabens along its southern side. Here, graben formation was accompanied by the small calk-alkalic to alkalic eruptions of the Powder River Volcanic Field (Fig. 1; Gehrels et al., 1980; Bailey, 1990).

Farther south, in east-central Oregon, the much wider (50 km) Oregon-Idaho graben (OIG) developed at circa. 15.3 Ma, following the initial eruptions of the flood basalts (Lees, 1994). The OIG is filled with small basalt to andesite to rhyolite eruptions and ash-flow tuffs of calc-alkalic to alkalic composition (Ferns et al., 1993; Lees, 1994; Binger, 1997; Cummings et al., 2000; Hooper et al., 2002a). In both the Eocene and the Miocene this extension-related calc-alkalic magmatism has been attributed to decompressional melting below a locally extended and thinned lithosphere. In addition, both the Harney Basin and the North Nevada Rift have been interpreted as the result of east-west extension (Fig. 1; Walker, 1979; Zoback et al., 1994).

Lawrence (1976) suggested that a series of parallel WNW-ESE lineaments across northern California, Nevada and Oregon were right-lateral strike-slip faults that increased the degree of extension from north to south. Mann (1989) and Hooper and Conrey (1989) subsequently interpreted the lineaments as broader pull-apart structures or right-lateral strike-slip extensional duplexes (Woodcock and Fischer, 1986), re-emphasizing an increase in the cumulative amount of extension from north to south across eastern Oregon. The structural details of the right-lateral strike-slip extensional duplexes are well displayed within the Oregon end of the Western Snake River Plain (WSRP; Fig. 5a).

The WSRP is a wide graben across which basalt/rhyolite contacts are progressively displaced westwards from north to south by a series of NW-SE right-lateral faults, the Vale Faults (Lawrence, 1976), that lie en-echelon to the WNW-ESE trend of the WSRP (Ferns et al., 1993). The amount of westward displacement to the south across the broad WSRP graben is recorded both by the displacement of the flood basalts and by the opening of the coeval, 50 km wide, Oregon-Idaho graben (OIG) along its southern side (the Adrian Fault; Ferns et al., 1993). The parallel but much smaller Malheur Gorge half graben, which lies south of the WSRP, has a similar structural pattern (Fig. 5a; Evans, 1990a, b). Rhyolite contacts are displaced right-laterally across the half graben which is characterized by NW-SE faults en-echelon to the WNW-ESE trending graben. North and south of the narrow half graben, north-south trending listric faults are well developed (Fig. 5a) which indicate that the regional direction of extension was east-west. East-west extension along the WNW-ESE trending zones results in the formation of narrow grabens or half grabens, as observed in both the wider WSRP and the much narrower Malheur Gorge half graben (Evans, 1990 a, b; Hooper et al., 2002b). Despite clear displacement of geologic contacts across the NW-SE faults in the WSRP and Malheur Gorge half graben, slickensides are lacking, an absence we attribute to the extensional, rather than the compressional, nature of the duplexes. The repetition of the geometry of the structural elements of these duplexes, most obviously the en-echelon arrangement of the NW-SE faults across the WNW-ESE trend of the structural zones, has led to the proposition that the Brothers Fault Zone (Walker and Nolf, 1981), the La Grande and Baker Grabens (Gehrels et al., 1980) and the southern side of the OWL (Swanson et al., 1980, 1981) are also extensional dextral strike-slip duplexes (Fig. 5; Hooper and Conrey. 1989; Hooper et al., 2002b).

In brief, the flood basalts erupted through the thinner accreted terranes along a line of fissures that parallel the cratonic margin immediately to the east. The tectonic setting was one of north-south compression, as the accreted terranes continued to be pressed northwards against the North American craton, and east-west extension which increased from north to south. Both the north-south compression and the increasing east-west extension southwards during the Miocene are consistent with current models of oblique subduction of the Juan de Fuca and Gorda plates beneath North America in which the increasing back-arc extension southwards has caused clockwise rotation of the Cascade arc (Magill et al., 1982; Wells and Heller, 1988; England and Wells, 1991; Wells et al., 1998; McCaffrey et al., 2000).

BASALT FLOW STRATIGRAPHY

Mapping of the CRBG over the last thirty years was initiated by Waters (1961) and later supported by paleomagnetic measurements and increasingly precise major- and trace-elemental analyses. The thick stack of basalt flows can now be broken down into subgroups, formations, members, and individual flows which can be recognized and mapped across the province as shown in figures 2 and 3 (Swanson et al., 1979; Mangan et al., 1986; Tolan et al., 1989; Reidel et al., 1989; Bailey, 1989a; Hooper, 2000).

Main Eruptive Phase: The Steens, Imnaha, Grande Ronde and Picture Gorge Basalts

The main phase of eruptions, from ~16.6 – 15.0 Ma, began in eastern Oregon and continued unabated over six paleomagnetic intervals. Eruptions started with the reverse magnetic sequence R_0, best displayed in the lower flows at Steens Mountain (Fig. 1; Mankinen et al., 1987), and continued through to the normal magnetic sequence (N_2) which forms the upper part of the Grande Ronde Basalt across the Columbia Plateau (Fig. 2). This main phase is characterized by a lack of regional unconformities between successive flows, unlike the younger formations.

***Steens Basalt**:*

This paper incorporates the lower Steens basalt into the CRBG as the informal basal formation of the flood basalt stratigraphy (Fig. 2). Upgrading the lower Steens basalt to formational status must await more detailed investigations to clarify its distinction, chemically and geographically, from the upper Steens basalt. $^{40}Ar/^{39}Ar$ dates, combined with local mapping and petrochemical correlations, suggest that the CRBG eruptions began at approximately 16.6 Ma in southeast Oregon in and around the Steens Mountain shield volcano (Fig. 1; Swisher et al., 1990; Binger, 1997; Hooper et al., 2002a; Camp et al., 2003). Johnson et al., (1998a) subdivided the 900 m Steens Mountain type section into the more primitive tholeiitic lower Steens tholeiitic basalt flows and the more evolved and mildly alkalic upper Steens basalt flows. This chemical break lies close to the R-N paleomagnetic transition of Mankinen et al. (1987).

In well-mapped areas near Malheur Gorge, northeast of Steens Mountain, Oregon (Figs. 1 and 5a), the lowest unit (lower Pole Creek) of the basalt of Malheur Gorge is the chemical and petrographic equivalent of the lower Steens basalt. The conformably-overlying upper Pole Creek and Birch Creek basalts are the chemical and petrographic equivalents of the Imnaha and Grande Ronde Basalts of the CRBG farther north (Fig. 6; Evans, 1990a, b; Ferns et al., 1993; Lees, 1994; Binger, 1997; Johnson et al, 1998b; Hooper et al., 2002a; Camp et al., 2003). Flows of lower Steens basalt composition extend over a large part of southeast Oregon (Fig. 1; Hart, 1982; Carlson and Hart, 1987, 1988). Flows similar to lower Steens basalt in magnetic polarity, petrography and chemical composition conformably underlie Imnaha Basalt as far north as the base of the Wallowa Mountains (C-1 sample of Carlson and Hart, 1988) and as far northeast as Squaw Butte, just north of Boise in Idaho (Martin, 1984; Hooper et al., 2002a).

Imnaha Basalt.

While the lower Steens basalt is largely restricted to the Oregon Plateau, the overlying Imnaha Basalt is the oldest formation of the CRBG in most of northeast Oregon and across the eastern Columbia Plateau (Kleck, 1976; Hooper et al., 1984). It thickens northwards from Malheur Gorge, where it lies conformably on the lower Steens basalt, across the northwest-trending Vale fault zone within the Western Snake River Plain graben to Farewell Bend (Fig. 1; Lees, 1994; Hooper et al., 2002a). Farther north it fills deep canyons eroded in Pre-Tertiary rocks, finally creating a flat lava plateau dipping gently west to northwest. North from its type sections in the Imnaha valley Imnaha Basalt is found in the Clearwater Embayment (Idaho), north to Pullman (Washington), and west to the eastern edge of the Pasco Basin, where it occurs at the base of drill core (Tolan et al., 1989).

Feeder dikes of Imnaha basalt occur in the southern part of the Chief Joseph dike swarm adjacent to the Imnaha valley, and south along the western side of the Snake River (Fig.1). Latest estimates (Tolan et al., 1989; Camp et al., 2003) suggest that Imnaha Basalt covered well over 50,000 km^2 with a volume exceeding 70,000 km^3. The most recent dates (Hooper et al., 2002a; Hooper, 2004) suggest ages for Imnaha Basalt between 16.5 and 15.0 Ma.

Grande Ronde Basalt (GRB).

Rocks of the Grande Ronde Basalt dominate the Columbia River flood basalt province, to form over 60% of the total volume of the CRBG (Camp et al., 2003). In contrast to the plagioclase-phyric Steens and Imnaha Basalts, flows of the Grande Ronde are, with few exceptions, aphyric tholeiitic basaltic andesites (52-57% SiO_2). GRB flows lie conformably on the Imnaha Basalt to form a thick and uniform sequence of typically flat-lying flows across the Columbia Plateau. These are well exposed in the deep modern canyons of the Columbia and Snake Rivers and their tributaries as they cross southeastern Washington and northeastern Oregon, and have been recovered from numerous exploratory boreholes in the search for gas and petroleum.

The thickness of the Grande Ronde Basalt increases progressively northward from Malheur Gorge in east-central Oregon to the Columbia Plateau. Flows extend as far north as Spokane in eastern Washington and they ponded in the actively deepening Pasco Basin in central Washington, where they reach their maximum thickness of >4 km (Reidel et al., 1989; 1994). Many overflowed the Basin and continued down the broad depression of the Columbia trans-arc lowlands (Beeson et al., 1989) across the rising volcanic arch of the Cascade Range to fill the Portland Basin and continue west to the Pacific Ocean (Fig. 1; Wells et al., 1989). Individual GRB eruptions are enormous, covering most of the Columbia Plateau with volumes up to 5,000 km^3 (Tolan et al., 1989; Reidel et al., 1989). The composite Sentinel Bluffs Member, which may include more than one contemporaneous eruption, exceeds 10,000 km^3 (Reidel, 2005).

$^{40}Ar/^{39}Ar$ ages are indistinguishable from those of the Imnaha Basalt, between 15.0 and 16.5 Ma, but the GRB are always stratigraphically the younger (Long and Duncan, 1982; Tolan et al., 1989; Hooper et al., 2002a; Hooper 2004). Feeder dikes of GRB composition occur throughout the Chief Joseph dike swarm, from Farewell Bend and Pedro Mountain in the south to the Washington-Idaho border (Fig. 1; Brooks, in press; Hooper and Reidel, in preparation).

The difficulty of subdividing this immense and compositionally uniform sequence of aphyric flows inhibited detailed work on the Columbia Plateau for many years. The problem was partially overcome in the 1970s by use of a portable fluxgate magnetometer. This recorded the basic magnetic polarity of each flow in the field and so allowed the GRB pile to be subdivided into four paleomagnetic units, from bottom to top: R_1, N_1, R_2, and N_2 (Fig. 2; Swanson et al., 1979), successive eruptions migrating northward with time (Camp, 1995). More detailed paleomagnetic measurements and mapping, combined with increasingly accurate chemical analyses (Fig. 3) for both major- and trace- elements, have subsequently allowed further subdivision of the GRB formation into individual members and flows (Mangan et al., 1986; Reidel et al. 1989).

Picture Gorge Basalt (PGB).

The relatively restricted Picture Gorge eruptions were contemporaneous with the Grande Ronde Basalt eruptions. PGB flows are confined to the John Day Basin south of the pre-Miocene WSW-ENE trending Blue Mountains uplift in north-central Oregon. The uplift parallels the southern side of the Klamath -Blue Mountains lineament (KBML of Riddihough et al., 1986), a gravity anomaly that marks the southeast margin of the Columbia Embayment (CE, Fig. 1). All PGB flows appear to have been fed through the Monument dike swarm in the John Day Basin and across the Aldrich Mountains immediately south (Fig. 1; Hooper and Reidel, in preparation). A few flows inter-finger with N_1-R_2 Grande Ronde flows across the uplift, which have been dated by Baksi (1989) at 16.1 ± 0.2 Ma (Nathan and Fruchter, 1974; Bailey, 1989a; Hooper et al., 1993). The succession of PGB flows is subdivided into three members and many individual flows (Bailey, 1989a). It covers 10,680 km^2 in the John Day Basin with a total volume of approximately 2,400 km^3 (Tolan et al., 1989).

Eckler Mountain Basalt.

The huge volumes of lower Steens, Imnaha, Grande Ronde and Picture Gorge Basalts of the main eruptive phase display no evidence of significant time intervals between flows, as would be indicated by erosion of lower units, the development of soil horizons or the presence of sedimentary interbeds. Flows of the main phase, therefore, appear to have poured out in rapid succession. A distinct hiatus, however, occurred in the eruptive record at the end of the Grande Ronde eruptions, across the whole Columbia Plateau. Saprolite horizons are present in southeast Washington where some lower flows of the next large formation, the Wanapum Basalt, are absent. Farther west this interval is occupied by sediments of the Ellensberg Formation eroded from the rising arch of the Cascade Range (Smith, 1988) and equivalent sediments occur locally around other margins of the plateau.

During this hiatus a few relatively small but distinctive flows of the Eckler Mountain Basalt were erupted between saprolite horizons along the eastern end of the Oregon-Washington border, each flow with its own feeder dikes. The primitive Robinette Mountain flow was followed by four flows of the Dodge Member, whose distinctive plagioclase- and olivine-phyric petrography, weathering characteristics, and chemical composition provide a useful marker horizon in local mapping (Ross, 1989; Hooper et al., 1995b).

Wanapum Basalt.

Eruption of larger flows resumed with the Wanapum Basalt which is dominated by flows of the Frenchman Springs, the Roza, and the Priest Rapids Members (Fig. 2). Each of these members is composed of multiple flows with a rather uniform chemical composition combining relatively low silica content with high abundances of TiO_2, P_2O_5 and other high field-strength trace elements (Fig. 3a). The many individual flows may be locally distinguished by characteristic phenocryst assemblages (Beeson et al., 1985; Martin, 1989). These large flows were interspersed with smaller, more evolved (higher incompatible elements) flows; the Lookingglass, Shumaker Creek, and Powatka flows (Figs. 2 and 3a). Wanapum Basalt flows are dated at 15.3 to 14.5 Ma (Tolan et al., 1989).

Saddle Mountains Basalt (SMB).

The youngest eruptions of the CRBG are the compositionally diverse flows of the Saddle Mountains Basalt, which represent the waning period of the flood basalt eruptions. As a consequence of their relatively small volumes and of an eruption period extending over 8 m.y. (approximately 14.5 to 6.0 Ma; Tolan et al., 1989) many SMB flows fill river canyons cut through previous flows and are referred to as "intracanyon flows" (Waters, 1961; Swanson et al., 1979). Because of their compositional diversity, virtually all the SMB flows can be distinguished from each other by chemical analyses (Fig. 3b) and correlated with their feeder dikes. Nearly all SMB dikes and flows are found along the northern end of the Chief Joseph dike swarm in and around the Lewiston basin (Hooper and Reidel, in preparation). The most northerly and youngest (8.5 Ma) known feeder dikes of the CRBG form the Ice Harbor linear vent system (Swanson et al., 1975) along the eastern margin of the Pasco Basin, although even younger flows of limited extent, the Tammany Creek and Lower Monumental flows (6 Ma), occur in the Lewiston Basin syncline (Figs. 1 and 2).

MODE OF EMPLACEMENT

The formation of sheet-flows, rather than more typical shield volcanoes, is the hallmark of a flood basalt province. As the viscosities of the CRBG flows and those of Hawaiian shield volcanoes are similar (Shaw and Swanson, 1970) the very different landscapes of the Columbia Plateau and the Hawaiian Islands must result from different modes of eruption and emplacement. Sheet-flows require large volumes of mafic magma extruded rapidly, typically from major fissures or feeder dikes, as in the case of the Columbia River basalts (Shaw and Swanson, 1970; Swanson et al., 1975). Such exceptionally voluminous and rapid eruptions require very large magma reservoirs, probably confined to the lower crust because of the compositions of their mineral phases (see below) and the lack of surface collapse structures.

How the sheet-flows were emplaced and the time required for the flows to cover such huge distances have proved controversial, with far reaching implications concerning the effect on world climate and on mass biological extinctions (Saunders, 2005). Shaw and Swanson (1970) originally proposed the rapid flow of lava across the gently sloping plateau surface; each flow, they argued, covered hundreds of kilometres in weeks or even days, a process requiring turbulent flow. More recent studies have suggested that emplacement took several months (Reidel and Tolan, 1992; Reidel, 1998) or even longer (Long et al., 1991). Self and his associates (Finnemore et al., 1993; Self et al., 1996, 1997) have compared the detailed physical characteristics of CRBG flows to other tholeiitic eruptions, particularly the much smaller flows of Hawaii. They concluded that laminar rather than turbulent flow dominated the CRBG eruptions and that, like many smaller flows on Hawaii, the CRBG flows were "emplaced as inflated compound pahoehoe flow fields via prolonged, episodic eruptions" (Self et al., 1997, p. 381).

Ongoing regional studies of compositional variation in vertical sections of individual sheet flows across the Columbia Plateau (Reidel, 1998, 2005) demonstrate a recurring pattern of older eruptive units forming the top and bottom of a composite sheet flow with younger eruptive units in the center. Examples (Fig. 7) include the Umatilla Member (Saddle Mountains Basalt, Fig. 2). In the central plateau the older Umatilla flow forms the top and bottom of the member while the younger Sillusi flow of the same member occupies the center (Fig. 7a). Both of these flows erupted from the same volcano in southeast Washington around which they also formed individual surface lobes. A second, more complex, example is the composite Cohassett sheet-flow of the Grande Ronde Basalt in the central plateau. In the vertical section across the sheet-flow (Fig. 7b) four individual compositional units are separated only by vesicular horizons with the oldest units at the top and bottom and progressively younger units towards the center. Each compositional unit forms individual surface flows nearer their eruptive centers in eastern Washington (Reidel, 2005). These profiles confirm that the predominant mechanism for growth of the sheet flows in the central plateau is by laminar flow with the progressive invasion and inflation of older lava units by younger. This conclusion is compatible with the variations in composition across some dikes recorded by Ross (1983), and with the very small decrease in temperature (Ho and Cashman, 1997), the lack of significant crystallization, and the consequent lack of chemical variation, from eruptive center to flow periphery, all properties which have long been recognized as characteristics of CRBG flows.

The time taken for these individual inflated sheet-flows to cover several hundred kilometres remains controversial. While Thordarson and Self (1998) suggest as much as 10 years to emplace the 300 km long Roza flow, Reidel (1998) calculates that the Umatilla Member, of similar length, could have been emplaced in weeks rather than years. Most recently, Keszthelyi et al. (2006) conclude that some of the CRBG flows could have been emplaced in weeks or months.

PETROGENESIS

Knowledge of the sequence and size of successive Columbia River basalt eruptions and the abundance of chemical and isotopic data which is now available place significant constraints on the sources and evolution of the lavas. The great volumes of basaltic lava that make up the CRBG require partial melting events in the mantle as the primary magma source. Isotopic data require additional source components from the lithosphere. In addition, variations within and between flows require some crystal fractionation at crustal pressures. Finally, physical mixing of magmas, both by recharge of evolving magma in lower crustal reservoirs and by physical mixing during eruption, can be clearly demonstrated in a number of cases. The relative significance of these various processes differs for each CRBG formation.

Primary Source Component:

Using trace-element and isotopic ratios, Hooper and Hawkesworth (1993), following Carlson (1984) and Church (1985) amongst others, showed that the CRBG as a whole falls into three discrete subsets, reflecting three distinct original sources (viz., negative correlations between Ce/Nb and Ce/Zr and between Ba/Nb and Nb/Y; Hooper and Hawkesworth, 1993, figs. 4-8). The subsets (Fig. 8) are assumed to mirror the same upper mantle melting processes that formed mid-ocean ridge basalt (MORB) from depleted mantle and ocean island basalt (OIB) from enriched mantle. The largest CRBG formations (lower Steens, Imnaha, Grande Ronde, and Wanapum Basalt Formations) suggest a primary mantle source akin to that for OIBs, a view consistent with Hawaiian-like trace-element profiles (Hooper and Hawkesworth, 1993), and with the Sr, Nd, Pb, and He isotopic ratios of the relatively uncontaminated Imnaha Basalt (Fig. 9; Dodson et al., 1997; Bryce and DePaolo, 2004). The Picture Gorge subset (Bailey, 1989b; Brandon et al., 1993) has trace-element and isotopic ratios which suggest that its primary source was more akin to depleted (MORB-type) mantle, similar to the younger basalts of eastern Oregon, including the high-alumina olivine tholeiites (HAOTs) of Hart and Carlson, 1987 and the Powder River Volcanic Field of Bailey, 1990. The third subset, the Saddle Mountains Basalt (SMB), has diverse chemical compositions and more evolved isotopic signatures (Fig. 9) which suggest an older, chemically variable, mantle source from beneath the cratonic crust of the Precambrian North American plate enriched more than 2000 Ma ago (Carlson, 1984).

***Other Source Components**:*

Fig. 8 also demonstrates the difference between, on the one hand, the Imnaha Basalt (and probably the lower Steens Basalt) which displays no enrichment in a lithospheric component as indicated by an increase in the Ba/Nb ratio and, on the other hand, both the Picture Gorge and Grande Ronde Basalts which do display clear enrichment in such lithospheric components (viz. positive correlations between Ce/Nb and Ce/Zr and variations of Ba/Nb without changes in Nb/Y (Fig 8; Hooper and Hawkesworth, 1993). As with the isotopic differences (Fig 9), the variability of ratios such as Ba/Nb are best explained by a mixing array between the original mantle component and a component with a lithospheric geochemical signature. The lithospheric component is characterized by conspicuous negative Ta-Nb anomalies (Hooper and Hawkesworth, 1993) and could represent either an enriched sub-continental lithospheric mantle (SCLM) or mafic lower crust. Hooper and Hawkesworth (1993) preferred the former explanation because of the limited fractionation of Sr/Zr observed in the silica-enriched Grande Ronde Basalt. Sr/Zr fractionation would be required in a partial melting of crust in the presence of plagioclase feldspar. Recent work on Re/Os isotopic ratios (Hart et al., 1997; Chesley and Ruiz, 1998) rules out an SCLM component in the Imnaha Basalt but suggests that a mafic component from the lower crust could be present. However, it is the Grande Ronde, not the Imnaha Basalt, which contains the obvious lithospheric component (Fig. 8). Both SCLM and lower crustal components may have been available, but the evidence at hand suggests that the lithospheric component forming the mixing arrays of the Grande Ronde and Picture Gorge Basalts was an enriched sub-continental lithospheric mantle.

Crustal Assimilation:

The earlier work of Carlson et al. (1981), Carlson (1984) and Carlson and Hart (1987) argued that the Grande Ronde Basalt was the combined result of crystal fractionation from different asthenospheric source magmas and assimilation of the upper crust. Assimilation of the upper crust was also suggested by Brandon et al. (1993) for the Picture Gorge Basalt. Arguments against a significant upper crustal component include the lack of any silicic magma which might be expected from such a process (DePaolo, 1983), while evidence from mineral phase-liquid investigations in the case of the Grande Ronde Basalt has led Caprarelli and Reidel (2004) to conclude (a) ".. very small pyroxene crystals preserving high P and T (i.e. lower crustal) information are an indication that magmas cannot have spent substantial amounts of time in shallow level (i.e. upper crustal) reservoirs" and (b) "Our thermobarometric determinations indicate a major role for a deep magma reservoir in the lower crust". Crustal contamination has also been demonstrated by recent laser analyses of the isotopic zoning of plagioclase phenocrysts in Imnaha and Picture Gorge Basalt magmas (Ramos et al., 2005). The combined results of these two studies suggest that both the pyroxene and plagioclase phenocrysts crystallized at approximately 25 km below the surface, a depth consistent with magma reservoirs near the base of the relatively thin crust of the accreted Blue Mountains terranes.

Crystal Fractionation and Magma Mixing:

The presence of phenocrysts in many CRBG flows, even in a few of the lower normally aphyric GRB flows, suggests that some crystal fractionation has occurred. This is confirmed by multiple chemical analyses of any one flow, which always shows a small spread of incompatible-element abundances at constant ratios (Fig. 3). All phenocryst assemblages are dominated by labradorite plagioclase, indicating their formation in the crust. Clinopyroxenes are next in abundance and, in the well-studied Grande Ronde Basalt

(GRB), these include both augite and pigeonite, while relatively Fe-rich olivine occurs occasionally in flows of other formations (Swanson et al., 1979; Reidel, 1983; Hooper et al., 1984; Bailey, 1989b). Caprarelli and Reidel (2004) demonstrate that the small pyroxene phenocrysts of the GRB grew in the lower crust from a dry basaltic magma.

Wright and his co-workers (Wright et al., 1989) have long maintained from their field and experimental studies that crystal fractionation was not a major factor in the evolution of the Grande Ronde Basalt and that the original magma was relatively Fe-rich. Hooper and Hawkesworth (1993) demonstrated that much of the variation within the Grande Ronde Basalt included changes in such ratios as Rb/Zr, which cannot be due to gabbro (crustal) fractionation, and they concluded that the maximum amount of gabbro fractionation observed within the GRB was less than 10%; the rest of the variation being due to mixing between the magma and the lithospheric components noted above. This restriction does not apply to the Imnaha Basalt, where a convincing case can be made for three groups of Imnaha basalt flows derived from three different degrees of partial melting of their single enriched mantle source, followed in each case by crystal fractionation and recharge (Fig10; Hooper and Hawkesworth, 1993). Modelling of major and trace elements has shown that much of the crystal fractionation observed in the Imnaha Basalt magmas included recharge of the magma reservoir by injection of new magma, a process that buffers the abundance of those major elements involved in the formation of the precipitated phenocrysts, while increasing the abundance of the incompatible elements (O'Hara and Mathews, 1981).

Finally, clear examples of the physical mixing of two chemically discrete magmas have been documented for Saddle Mountain Basalt flows, both prior to eruption (Hooper, 1985) and after eruption (Reidel and Fecht, 1987). Physical mixing processes are best detected when the two end-member flows have distinctive compositions, but it could be anticipated that, during the large and rapid eruptions of the chemically similar GRB flows, physical mixing of magmas occurred both before and after eruption.

DISCUSSION: PLUME VS. NONPLUME

The most fundamental problem confronting workers on the CRBG is whether this and other flood basalt provinces are derived from a deep-mantle plume or from some shallow-mantle process. Workers on the Oregon Plateau have long advocated a model of volcanism associated with back-arc extension related to the Basin and Range Province to account for the Steens and younger (HAOT) lavas (Eaton, 1984; Hart and Carlson, 1987; Carlson and Hart, 1988). In contrast, Draper (1991) was first to suggest that these basalts have a mantle-plume origin. Contrasting views are also apparent for eruptions along the Snake River Plain, which have been attributed to both a mantle-plume process (Duncan, 1982; Draper, 1991; Pierce and Morgan, 1992) and to shallow-mantle nonplume processes (King and Anderson, 1998; Humphreys et al., 2000; Christiansen et al. 2002).

Scrutiny of nonplume interpretations and the need for a unified model

Most workers with direct field experience of the Columbia River basalts have embraced a mantle-plume origin as the most plausible explanation for the exceptional volume of basalt erupted in a very short time and over a very restricted area; 220,000 km^3 in approximately 1.5 million years (Brandon and Goles, 1988; Hooper and Hawkesworth, 1993; Takahahshi et al., 1998; Hooper et al., 2002a; Camp et al., 2003; Camp and Ross, 2004). Camp and Ross (2004) emphasize the need for a unifying model encompassing all contemporaneous magmatism on the Colombia Plateau, Oregon Plateau, the Snake River Plain and Northern Nevada Rift, and they note that only the plume model achieves this.

Nonplume interpretations appear to require explanations for the main-phase flood basalt eruptions independent of those for the eastern Snake River Plain and the Oregon Plateau. Such interpretations describe long-lived lived tectonic regimes and slowly evolving processes that fail to account for the sudden outburst and short duration that typifies flood-basalt volcanism.

It is not clear, for example, why in the King and Anderson (1998) model, the exceptionally large volumes of homogeneous CRBG tholeiite should erupt at only one point along the cratonic margin, which runs from Alaska to California, if eruptions were controlled, as they argue, by the difference in thickness between the craton and adjoining lithosphere. Christiansen et al. (2002) suggest the eruptions may have been controlled by older structures beneath the Eastern Snake River Plain and the Brothers Fault Zone, which cross the cratonic margin close to the original center of the flood basalt eruptions. While accepting the presence of these older structures and their ability to guide the location of later volcanicity, many equally significant structures meet the cratonic boundary to the north and south, yet fail to generate huge volumes of flood basalt. The problem of explaining such sudden, short-lived, and voluminous eruptions at one particular location remains, unless the additional presence of a thermal anomaly is invoked. Christiansen et al (2002) also object to the plume model because it requires the coincidence of having the hot spot track follow an older tectonic boundary. The real coincidence, however, is between the older tectonic boundary and the westward migration of the North American plate, as derived independently from plate motions, regardless of whether a mantle plume is present.

Nonplume models that rely solely on back-arc extension (Carlson and Hart, 1988; Smith, 1992) fail to take into account the field, petrographic and chemical evidence of the two distinct tectonomagmatic events that are particularly evident in east-central Oregon (Fig. 4; Hooper et al., 2002a): (1) long-lived, small-volume calc-alkaline to alkaline volcanicity of basalt through rhyolites and silicic tuffs which are specifically associated with graben formation (Hooper et al., 1995a), and (2) the huge and short-lived, relatively homogeneous, flood-basalt eruptions. The former is consistent with a long-lived period of back-arc extension, but the latter is more reasonably attributed to the abrupt appearance of a thermal anomaly, consistent with plume emplacement. Being in part contemporaneous, these two events inevitably affected each other. Following the plume model, the thin lithosphere of the accreted terranes would have facilitated both rapid rise of the plume head and decompressional partial melting (White and McKenzie, 1989, 1995). Surface eruption would be aided by the ability of the magmas to find the weakest (thinned) zones (Thompson and Gibson, 1991) along highly oriented fissures aligned perpendicular to the direction of long-lived back-arc extension above the plume head. Under this scenario, the elevated potential temperature of the plume head would have both weakened and uplifted the lithosphere leading to increased east-west extension along the crest of the elevated region so forming the Northern Nevada Rift (Zoback et al., 1994; Glen and Ponce, 2002), the concentration of feeder dikes of the Chief Joseph swarm along the crest of the uplift, and the subsequent development of the unusually wide Oregon-Idaho graben.

The derivation of the CRBG lavas by extension alone is also in direct conflict with the experimental results of McKenzie and Bickle (1988) and White and McKenzie (1989, 1995). These studies demonstrate that the surface eruption of continental flood basalts requires both a mantle source with abnormally high potential temperatures (T_p), together with high stretching factors (β) typical of advanced stages of continental extension. Extension alone, no matter how advanced, cannot generate the melt volumes typical of continental flood basalt provinces. On the other hand, field evidence shows that at least some flood basalt provinces, like the Deccan, have been generated prior to significant extension (Hooper, 1990), suggesting that high potential temperatures play the more critical role in melt generation on such a massive scale.

Merits of the plume model

Several lines of evidence support a mantle-plume genesis for the CRBG eruptions. The earliest CRBG flows contain the chemical and isotopic signatures of ocean island basalts (Hooper and Hawkesworth, 1993; Bryce and DePaolo, 2004), a similarity required if a plume model is to be sustained. In common with magmas from the Snake River Plain, these early CRBG flows also have the high $^{3}He/^{4}He$ ratios (11.4 ± 0.7 Ra) expected of basalts derived from a deep mantle source (Dodson et al., 1997; D. Graham, pers. comm.. 2003).

The recent identification of a plume-tail beneath Yellowstone National Park to a depth of 600 km (Yuan and Dueker, 2005; Smith et al., 2005) appears to verify a plume origin for Yellowstone and the Snake River Plain hotspot track. Plate reconstructions along this linear belt of age-progressive rhyolitic centers unambiguously places this plume tail near the McDermitt caldera along the Oregon-Nevada border at ~16-17 Ma, coincident in both time and space with the earliest CRBG eruptions. To accept a nonplume origin for the flood-basalt event requires acceptance that the Miocene location of the plume tail at the initiation site of flood-basalt volcanism is a coincidence, and incidental to a separate shallow-mantle process responsible for the flood-basalt event. We suggest it is more probable that the McDermitt region separates flood-basalt volcanism to the north, underlain by the plume head, from the Yellowstone hotspot track to the east, underlain by the plume tail. The plume-head/plume-tail duality is consistent with the temporal and spatial relationships inherent in traditional plume models (Morgan, 1981; Richards et al., 1989;

Campbell and Griffiths, 1990: Griffiths and Campbell, 1991; Hill et al., 1992; Weinberg, 1997).

The unusually high elevation of the extended terrain of eastern Oregon (approx. 1 km a.s.l.) is difficult to explain in the absence of elevated mantle temperatures. White and McKenzie (1989, 1995) show that as β values (extension) increase in lithosphere underlain by normal mantle T_p, continental subsidence will increase accordingly. However, if the mantle T_p is elevated to 150°C or more above normal, uplift will ensue, even at β values as high as 5 (White and McKenzie, 1995). Such uplift results from mantle melting and the addition of new crust, together with the reduced density provided by both the thermal anomaly and the residual mantle (Humphreys et al., 2000). A more buoyant lithosphere in the intermontane Pacific Northwest is consistent with findings of both Parsons et al. (1994) and Saltus and Thompson (1995) who modelled a residual mass deficit in the mantle beneath this uplifted region. Both studies concluded, independently, that the high altitude of this extended terrain must be isostatically supported by a broad mass of hot, low-density mantle which, they argue, is the Yellowstone mantle-plume head.

One problem commonly cited against a mantle-plume genesis is the location of the main-phase eruptions from the Chief Joseph and Monument dike swarms up to 400 km north of the presumed impingement of the hotspot near the Oregon-Nevada border at ~16-17 Ma. This apparent inconsistency in the plume model has been addressed by both Geist and Richards (1993) and Camp (1995). Geist and Richards (1993) suggested that the plume head was initially deflected beneath the Chief Joseph dike swarm by the northeast subducting Farallon plate at ~17 Ma, followed by rapid recovery of the plume tail to the western end of the Snake River Plain at ~14 Ma. Alternatively, Camp (1995) suggested that the spreading plume head was distorted against the thick cratonic margin of North America, deflecting it largely to the north beneath the progressively thinner lithosphere of the Blue Mountains accreted terranes. Northward flow of this hot mantle to shallower levels, it was argued, was accompanied by plume-generated uplift and decompressional melting.

Uplift above the plume head is one of the principal predictions of a plume model (White and McKenzie, 1989, 1995; Campbell and Griffiths, 1990) and such uplift immediately before and during the CRBG eruptions is evident from the deep canyons in the pre-basalt surface along the Idaho-northeast Oregon border; canyons which were filled by the initial flows of Imnaha Basalt (Kleck, 1976; Hooper et al., 1984; but see Hales et al. 2005, for an alternative view). The continued development of a northward dipping paleoslope during the main eruptive phase (Hooper and Camp, 1981; Camp, 1995; Camp and Ross, 2004) means that this uplift continued during the flood basalt eruptions. Major uplift above the erupting fissures is also consistent with both paleobotanical altitude estimates and the development of a broad precipitation shadow to the east which peaked at about 15 Ma (Pierce et al., 2002).

A plume genesis provides a unifying model capable of explaining all magmatic activity centered on east-central Oregon and contemporaneous with the CRBG eruptions from 17-6 Ma (Camp and Ross, 2004). The model includes magmatism along the eastern Snake River Plain, the Northern Nevada Rift system, and the Brothers fault zone. Camp and Ross (2004) argue that the main-phase eruptions migrated progressively outwards, from southeastern Oregon northwards along the Chief Joseph and Monument dike swarms, and southwards into the eastern graben of the Northern Nevada rift. Like spokes on a wheel, the focal point of these three outwardly radiating trends is close to the projected center of the mantle plume at ~16-17 Ma, as would be predicted from impingement and rapid spreading of a starting plume head (Campbell and Griffiths, 1990). The main-phase eruptions ceased at ~15 Ma when the plume head was sheared off by the thick westwardmoving cratonic margin, thus severing the plume-head from the feeding plume tail (Pierce and Morgan, 1992; Camp and Ross, 2004). At ~14 Ma, rhyolites began to erupt above the plume tail in southwestern Idaho, followed by the migration of bimodal eruptions along the Snake River Plain hotspot track (Pierce et al., 2002). Meanwhile the plume head, prevented from expanding east or farther north by the cratonic margin (Fig. 1), expanded west and south to form the westward-migrating bimodal eruptions along the Oregon High Lava Plains (Camp and Ross, 2004; Jordan et al., 2004), and the mixed eruptions associated with the Northern Nevada Rift (John et al., 2000), respectively.

The plume model we advocate is based on the experimental work of Campbell and Griffiths (1990), Cordrey et al. (1997), Takahahshi et al. (1998) and Yaxley (2000) amongst others, in which crustal basalt is subducted deep into the mantle, perhaps but not necessarily, to the core-mantle boundary, where it is re-activated to rise again as an eclogite-rich plume, the large head of which eventually spreads out beneath the lithosphere. Experimental work indicates that such an iron-rich mantle source is capable of creating the large volumes of relatively evolved basaltic magma, without significant quantities of silicic differentiates or mafic cumulates. Wright et al. (1979, 1989) have argued that the Grande Ronde Basalt, in particular, required an unusually iron-rich mantle source as would be available in an eclogite-rich mantle plume (Takahahshi et al., 1998; and Yaxley, 2000). Rapid mantle flow, decompressional partial melting, and uplift, all occurred in an environment of a relatively thin lithosphere and back-arc extension. This generated highly oriented north-south feeder-dikes, with most of the basalt erupted from the Chief Joseph dike swarm to produce the greatest volume of CRBG magma in only ~1.5 m.y.

Our conclusion is that nonplume models, such as back-arc spreading, mantle-upwelling adjacent to a cratonic margin, or generation of magmas along older tectonic boundaries, are not, in themselves, capable of explaining the ultimate cause of the

Columbia River flood-basalt eruptions. A thermal anomaly is required. We believe that an eclogite-rich plume emplaced into a tectonic environment of a thinner lithosphere and accompanied by active extension, provides a model that more readily accounts for the salient features of this flood-basalt province, including the unusually rapid extrusion of such exceptionally large volumes of evolved basaltic magma.

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FIGURE CAPTIONS

Fig. 1. Map of the Columbia River flood basalt province (shaded), including the lower Steens Basalt interpreted as the oldest flood basalt unit, modified from Camp and Ross (2004). Note that in the graben of the Western Snake River Plain (WSRP), east-central Oregon, flood basalts are only present at depth along the northern margin and, while flood basalts are shown beneath the Oregon-Idaho graben (OIG), their presence there has not been proven. SCF= Straight Creek Fault; SB=Snoqualmie Batholith; SCR= southern Cascade rift; CE=Columbia Embayment; PB= Pasco Basin; Y= Yakima fold belt; HF= Hite Fault (down to the west, but with minor post-basalt left-lateral displacement); L=Lewiston and the Lewiston Basin syncline; LF= Limekiln Fault (down to the west but with minor post-basalt left-lateral displacement); BMA=Blue Mountains anticline; TBS=Troy Basin syncline; CJ= chief Joseph dike swarm; LG= La Grande graben; BG= Baker graben; W=Wallowa Mountains horst; KBML= Klamath-Blue Mountains lineament (Riddihough et al., 1986); BMU=Blue Mountains Uplift; M= Monument dike swarm; F= Farewell Bend on the Snake River; VF=Vale fault zone; BFZ= Brothers fault zone; EDFZ= Eugene-Denio fault zone; MFZ= McLaughlin fault zone; HB=Harvey Basin; MG=Malheur Gorge; MC= McDermitt caldera.

Fig. 2. Stratigraphy and nomenclature of the Columbia River flood basalt province. Modified from Tolan et al. (1989).

Fig. 3. Chemical distinctions between CRBG formations, members and flows. (a) TiO_2 vs P_2O_5 plot of Imnaha, Grande Ronde, Eckler Mountain and Wanapum Formations; the "Ti

gap" separates all lower formations from the overlying Wanapum Basalt. Ter=Robinette Mountain flow (Eckler Mt. Fm.); Tgfs=Field Springs flow (Grande Ronde Fm.); Ted=Dodge flows (Eckler Mt. Fm.). Wanapum Basalt flows are : Tlg=Lookingglass flow; Tsh=Shumaker Creek flow; Tpow=Powatka flow; Tr=Roza Member; Tpr=Priest Rapids Member; Tfs=Frenchman Springs Member. (b) TiO_2 vs P_2O_5 plot of individual flows within the Saddle Mountains Basalt Formation. Note how multiple analyses of each flow forms a short array at constant P2O5/TiO2 ratios, suggesting gabbro fractionation. Ta=Asotin; Tp=Pomona; Twc=Cloverland; Tw=Wilbur Creek; Tb=Buford; Tws=Slippery Creek; Twl=Lewiston Orchards; Tlm=Lower Monumental; Tim=Martindale; Tesq=Esquatzel; Twt=Tenmile Creek; Tem=Elephant Mountain; Tu=Umatilla; Tib=Basin City; Tn= basalt of Eden; Tig=Goose Island flow. The Umatilla Member includes two eruptions, the Umatilla flow followed by the Sillusi flow from the same vent, the younger invading and inflating the older in the central Plateau as shown in Figure 7 (after Hooper, 2000).

Fig. 4. Eruption rates of the tholeiitic flood basalts (Steens [shaded] , Imnaha, Grande Ronde, Wanapum, and Saddle Mountains Basalts below the dashed line) contrasted with the eruption rates of the small scale calc-alkalic to alkalic volcanicity (black) associated with active extension in east-central Oregon. (after Hooper et al., 2002a).

Fig. 5. Right-lateral extensional duplexes or 'pull-apart' structures in eastern Oregon**. (a)** Cartoon of the structural elements of the Western Snake River Plain (WSRP, Fig. 1) graben in east-central Oregon, including the Vale Faults (VF), the Malheur Gorge half-graben (MGG), and the western margin of the Oregon-Idaho graben (OIG) defined by the rhyolite (stippled) intruded along the graben boundary faults. a=WNW-ESE faults bounding the two grabens: these faults displace rhyolite contacts right-laterally

both across the MGG and across the southern boundary fault (Adrian Fault) of the WSRP graben; b=NW-SE faults, within the grabens, which displace rhyolite right-laterally across the Vale Fault (VF) zone; c=displaced rhyolite contacts (stippled); d=N-S listric faults between the grabens and to the south of the MGG which define the direction of extension as east-west. (modified from Hooper et al., 2002b). **(b)** Fault pattern along part of the southern margin of the Olympic-Wallowa lineament (OWL, Fig. 1) on the Washington-Oregon border as mapped by Swanson and Wright (Swanson et al., 1980, 1981), showing a similar structural geometry to Fig. 5a**. (c)** Faults along the Brothers Fault (Fig. 1) zone as mapped by Walker and Nolf (1981), again showing a structural geometry similar to that of Fig 5a. **(d)** Theoretical right-lateral extensional duplex, after Woodcock and Fischer (1986).

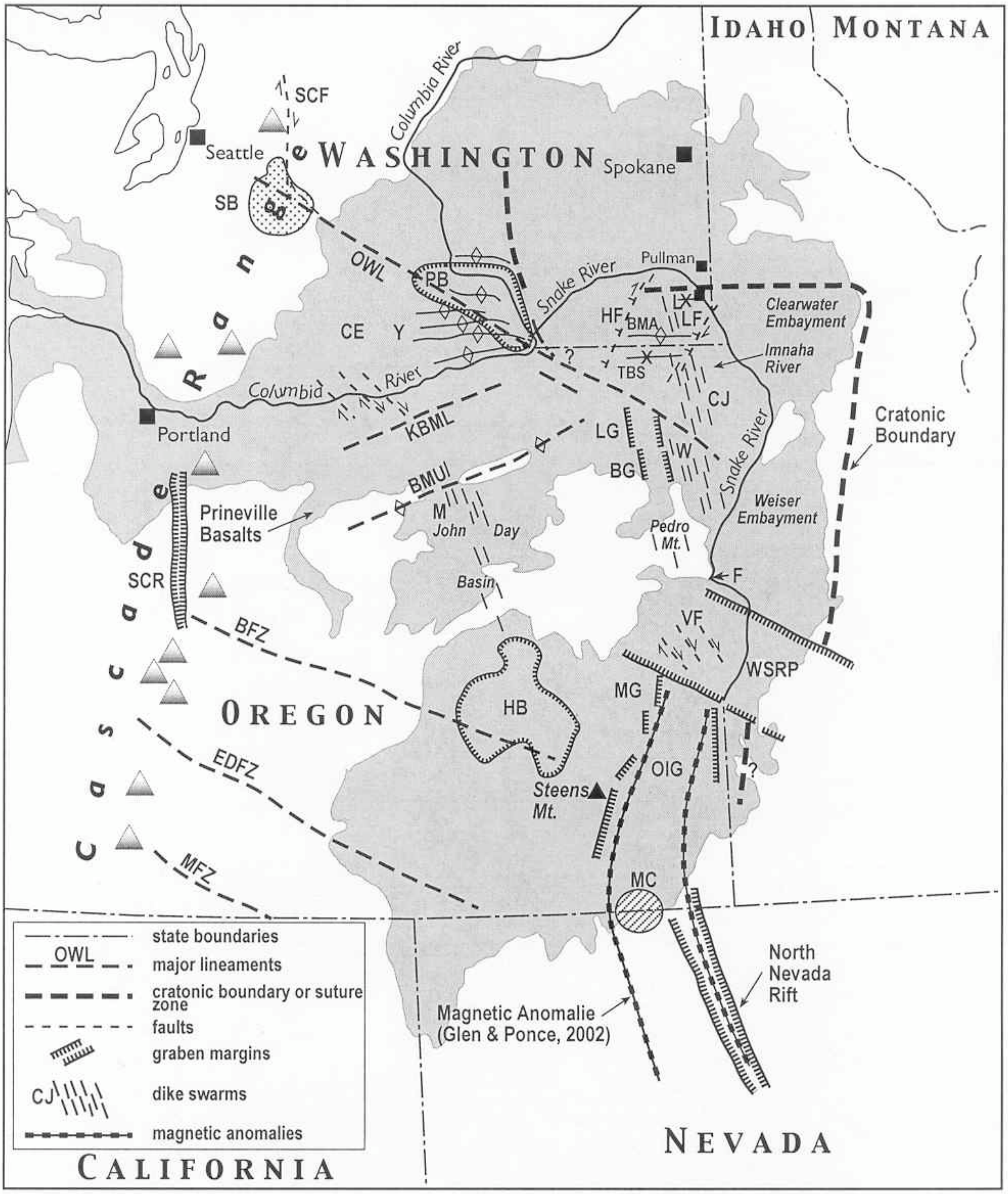
Fig. 6. Schematic cross section of volcanic units from Steens Mountain to Malheur Gorge, east-central Oregon. Lower Steens Basalt (lower Pole Creek) is conformably overlain by Imnaha Basalt (upper Pole Creek) and Grande Ronde Basalt (Birch Creek). (after Camp et al., 2003).

Fig. 7. Chemical variation across vertical sections of composite sheet-flows of the central Columbia Plateau, illustrating invasive intrusion and inflation of older by younger lavas. (a) Umatilla Member, Saddle Mountains Basalt; the Umatilla flow erupted before the Sillusi flow from the same volcanic fissure and vent in southeast Washington. (b) Cohassett composite flow, Grande Ronde Basalt; the four chemical compositions were erupted from discrete fissures/vents in southeastern Washington; chemical types from oldest to youngest are: CC=California Creek; AH=Airway Heights; SC=Stember Creek; SF=Spokane Falls. (after Reidel, 1998, 2005).

Fig. 8. Trace element ratios used to discriminate primary and secondary sources for Columbia River basalt formations. (a) Ce/Zr vs. Ce/Nb; (b) Nb/Y vs. Ba/Nb. Stars=mantle sources, MORB is mid-ocean ridge basalt source, PM is primitive mantle, OIB is ocean island basalt source; PGB (filled triangles)=Picture Gorge Basalt; LSt (plus signs)=Lower Steens basalt; IM (open squares)=Imnaha Basalt; GRB (filled squares)=Grande Ronde Basalt; W (open triangles)=Wanapum Basalt; SMB (crosses)=Saddle Mountains Basalt. (modified from Hooper and Hawkesworth, 1993). The proximity of some formations (L. Steens, Imnaha, Grande Ronde, and Wanapum) to OIB source compositions is used as evidence that these formations were derived from an enriched, OIB-like, mantle source. In contrast, proximity of the Picture Gorge Basalt (and high alumina olivine tholeiites and basalts from the Powder River volcanic field, not shown) to MORB source compositions is used as evidence of their derivation from a depleted MORB-like mantle. Increase in Ba/Nb ratios and arrays formed from positive correlations between Ce/Nb and Ce/Zr in the Picture Gorge and Grande Ronde Basalts are interpreted as mixing arrays between the primary mantle source components and a secondary lithospheric source, while the lack of similar trends in the Imnaha and lower Steens basalt implies that these formations were not significantly affected by addition of such a lithospheric component and their chemical variation can best be explained by variable degrees of partial melting and gabbro fractionation as seen in figure 10.

Fig. 9. Sr and Nd isotope ratios for the CRBG. MORB (vertical lines field)=Mid-ocean ridge basalt; OIB (blank field)=ocean island basalt; HAOT (open triangles)=high alumina olivine tholeiite; Picture Gorge Basalt (closed triangles); Imnaha Basalt (open squares); Grande Ronde Basalt (closed squares); Eckler Mountain Basalt (closed diamonds); Wanapum Basalt (open circles); Saddle Mountains Basalt (crosses). (From Hooper and Hawkesworth, 1993).

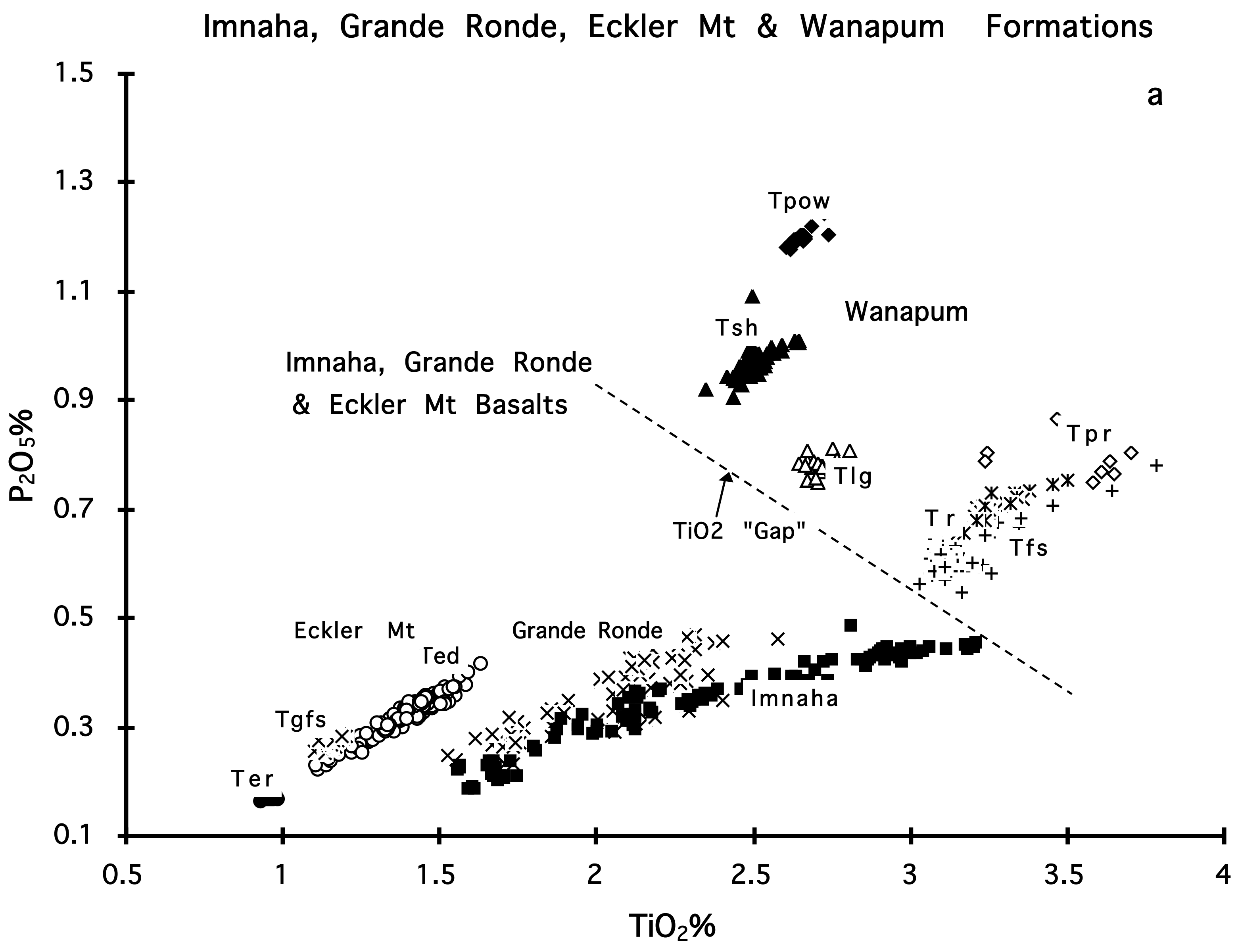
Fig10. Evolution of Imnaha Basalt flows. (a), (b) and (c) all illustrate three discreet groups of Imnaha Basalt and both (a) and (b) show how these may be formed by variable degrees of partial melting of an enriched mantle. Each group has then undergone crystal fractionation and recharge in lower crustal reservoirs. P.M.= partial melting trend; F.C.= fractional crystallization trend; RC=Rock Creek type of Imnaha Basalt; AB=American Bar types of Imnaha Basalt. (after Hooper and Hawkesworth, 1993).


IDAHO
MONTANA
WASHINGTON
OREGON
NEVADA
CALIFORNIA
Seattle
Spokane
Pullman
Portland
SCF
SB
OWL
PB
CE
Y
Columbia River
Snake River
KBML
BMU
M
John Day Basin
LG
BG
W
CJ
HF
BMA
LX
LF
TBS
Clearwater Embayment
Imnaha River
Cratonic Boundary
Weiser Embayment
Pedro Mt.
F
VF
WSRP
MG
OIG
HB
Steens Mt.
MC
Prineville Basalts
SCR
BFZ
EDFZ
MFZ
Cascade Range
North Nevada Rift
Magnetic Anomalie (Glen & Ponce, 2002)
state boundaries
major lineaments
cratonic boundary or suture zone
faults
graben margins
dike swarms
magnetic anomalies

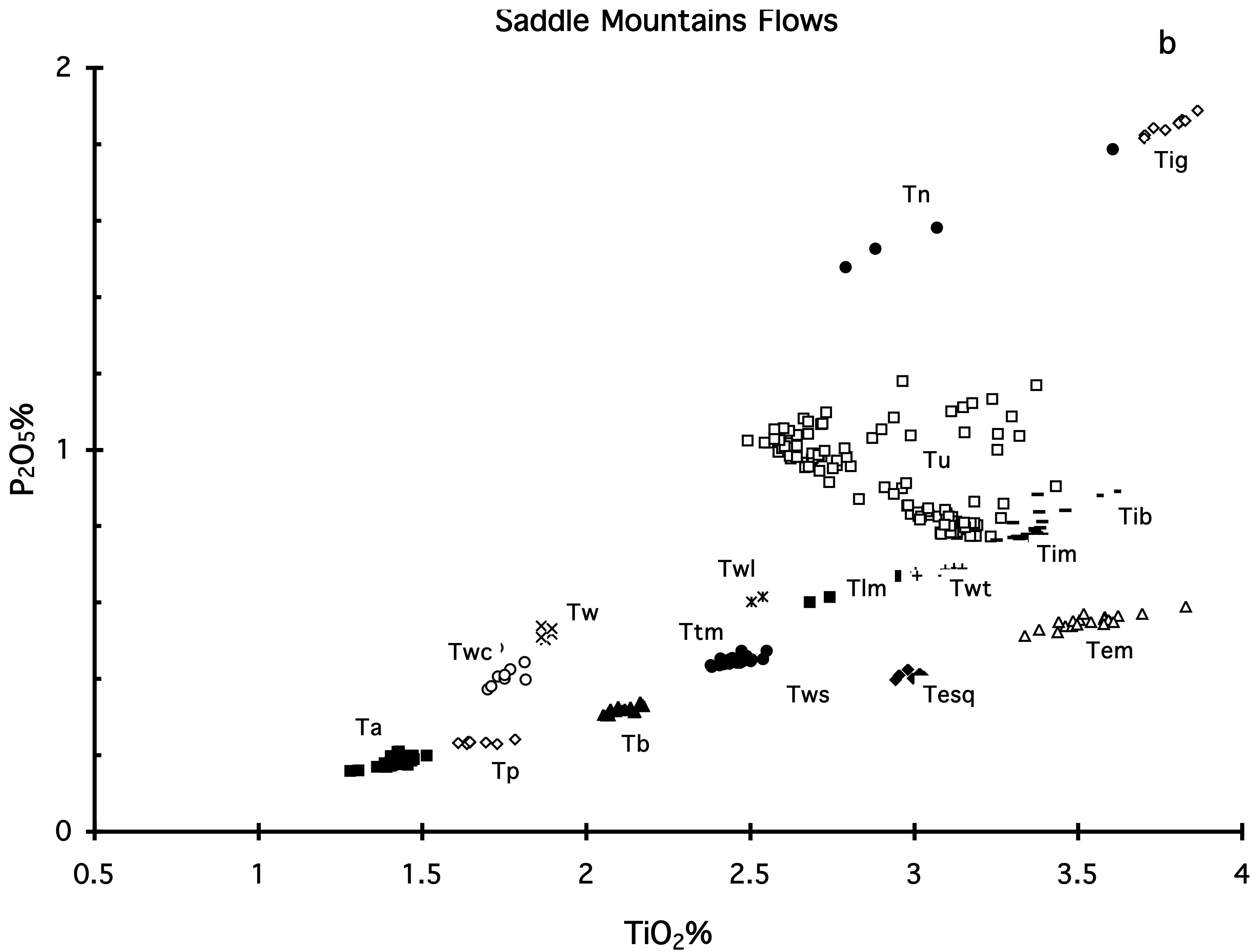
Stratigraphy and Nomenclature of the Columbia River Flood Basalt Province

	Formation	Member	Other Units*	Isotopic Age (Ma)	Estimated Volume (Km_)	Magnetic Polarity
Columbia River Basalt Group		Lower Monumental		6 [1]	15	N
		Ice Harbor		8.5 [1]	75	N,R,N
		Buford	Swamp Creek		20	R
	Saddle	Elephant Mountain	Craigmont	10.5 [1]	440	R,T
	Mountains	Pomona	Grangeville	12.0 [1]	760	R
	Basalt	Esquatzel	Icicle Flat		70	N
		Weissensels Ridge			20	N
		Asotin			220	N
		Wilbur Creek			70	N
		Umatilla			720	N
		Priest Rapids		14.5 [1]	2,800	R
	Wanapum	Roza			1,300	T
	Basalt	Shumaker creek				N
		Frenchman Springs	Powatka	15.3 [1]	6,410	N
		Lookingglass				
		Hiatus with saprolite horizon				
	Eckler	Dodge				N
	Mountain				170	
	Basalt	Robinette Mountain				N
		Hiatus with saprolite horizon				
Main Phase				15.0 [3]		N2
	Grande				GRB=148,600**	R2
	Ronde		Picture Gorge			
	Basalt		Basalt		PGB= 2,400	N1
						R1
	Imnaha				10000**	N0
	Basalt					
	Lower					
	Steens					
	Basalt			16.6 [2,3]	60000**	R0

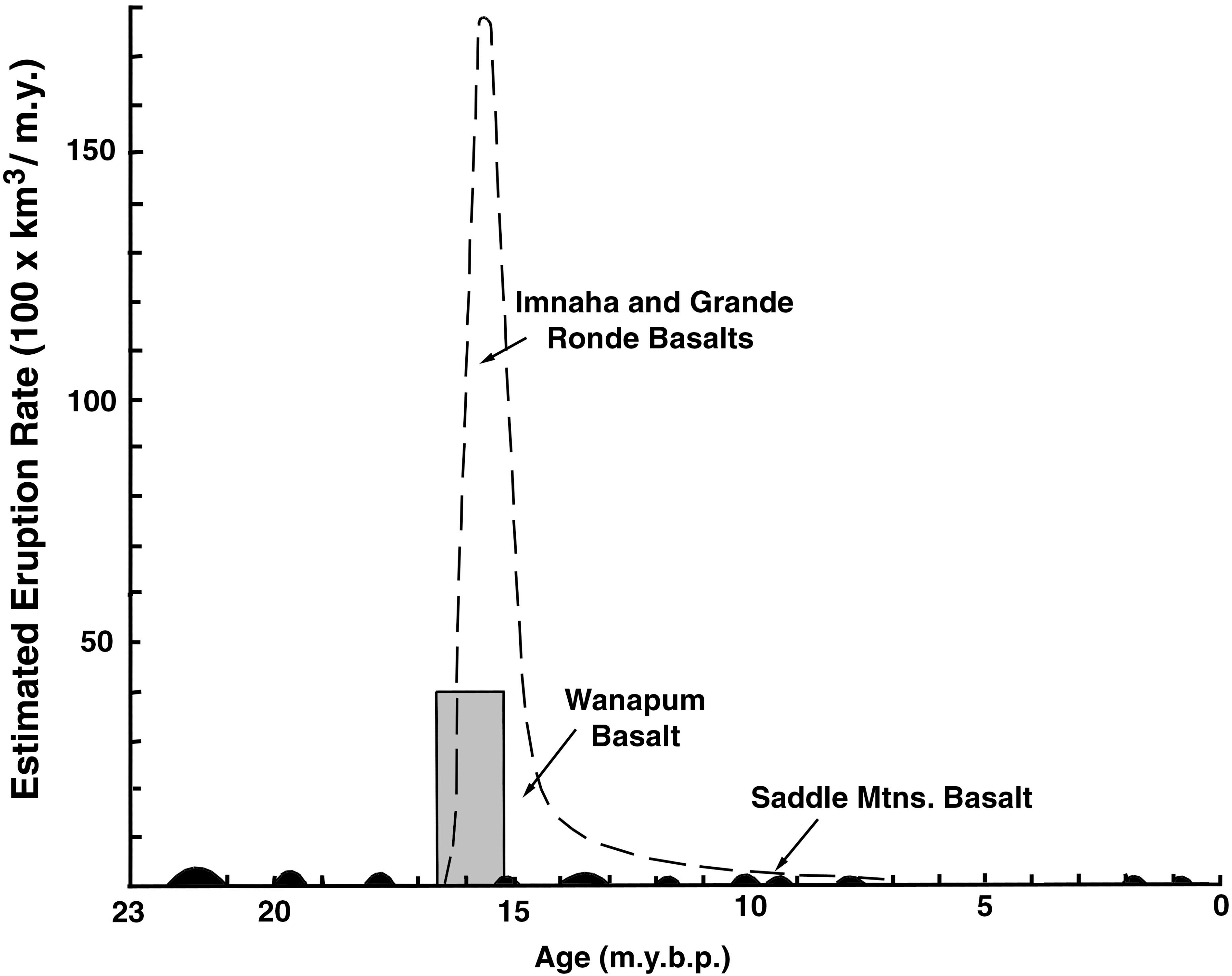
* Isolated units whose stratigraphic position is only approximate
** Camp et al., 2003
Age sources
[1] Tolan et al., 1989
[2] Swisher et al., 1990
[3] Hooper et al., 2002; Hooper, 2004.



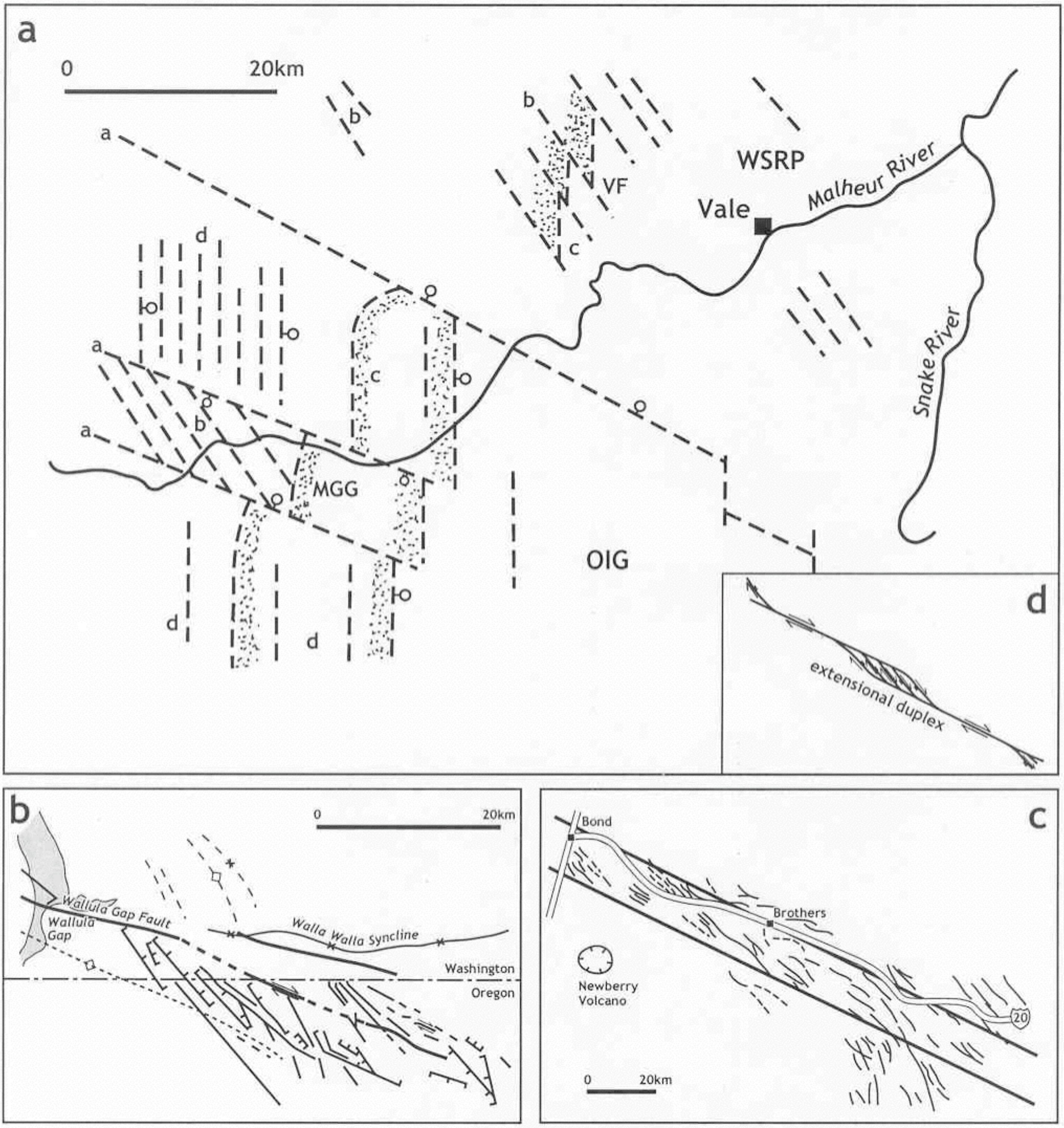
Imnaha, Grande Ronde, Eckler Mt & Wanapum Formations
a
Tpow
Wanapum
Tsh
Imnaha, Grande Ronde
& Eckler Mt Basalts
Tpr
Tlg
TiO2 "Gap"
Tr
Tfs
Eckler Mt
Ted
Grande Ronde
Imnaha
Tgfs
Ter
P2O5%
TiO2%
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
0.5
1
1.5
2
2.5
3
3.5
4



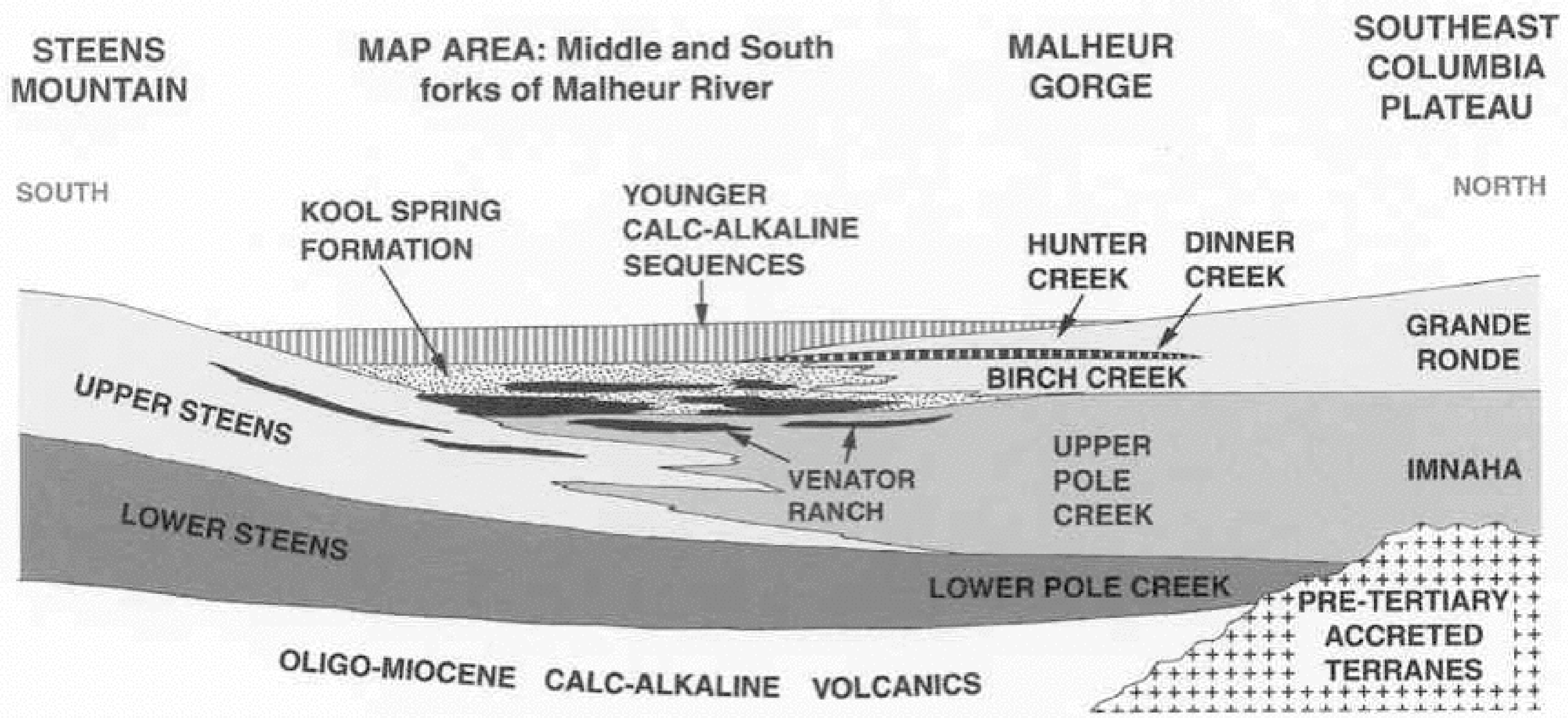
Saddle Mountains Flows
b
2
1
0
P2O5%
0.5
1
1.5
2
2.5
3
3.5
4
TiO2%
Tig
Tn
Tu
Tib
Tim
Twl
Tlm
Twt
Tw
Ttm
Twc
Tem
Tws
Tesq
Ta
Tb
Tp



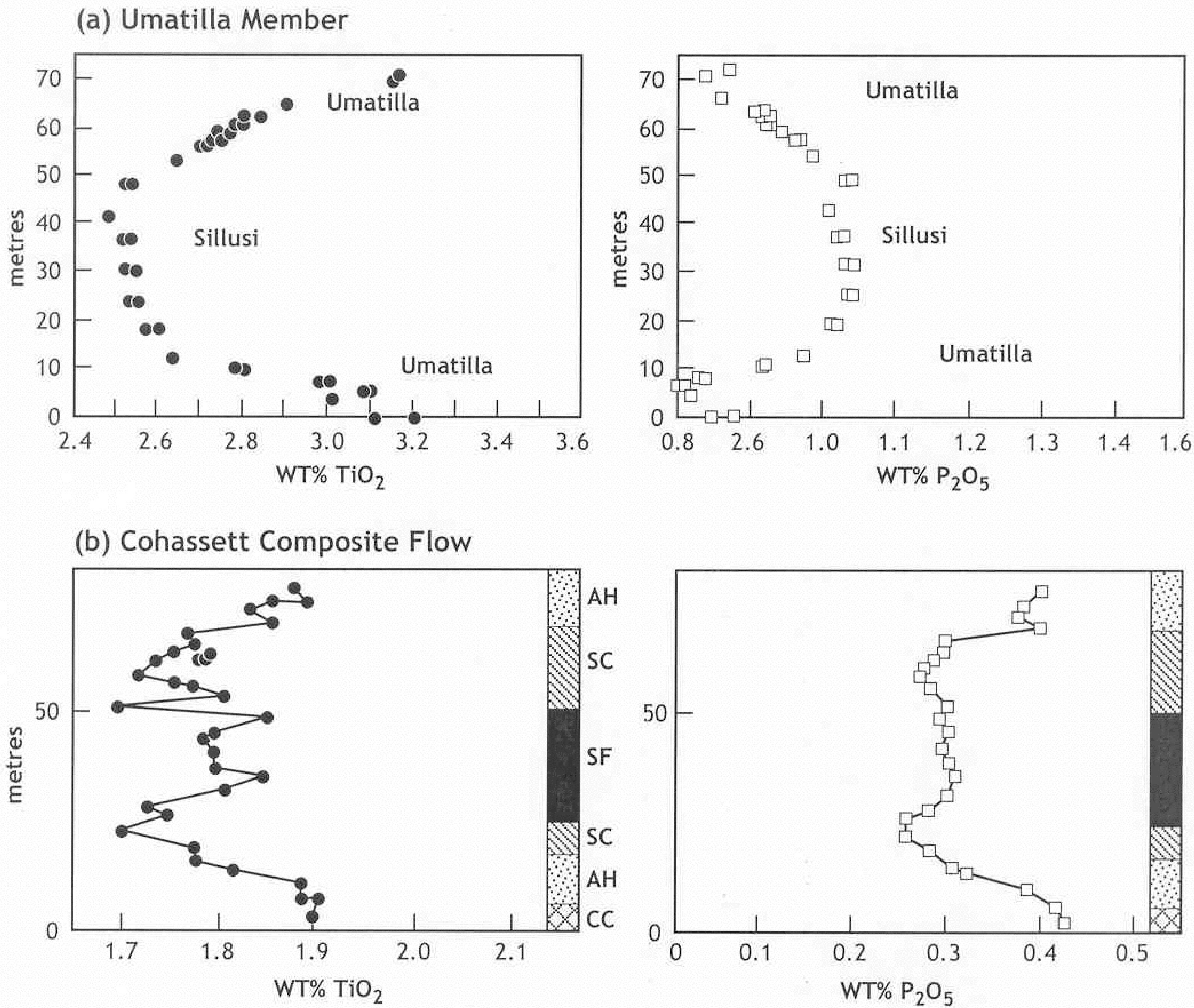
Estimated Eruption Rate (100 x km3/ m.y.)
150
100
50
Imnaha and Grande
Ronde Basalts
Wanapum
Basalt
Saddle Mtns. Basalt
23
20
15
10
5
0
Age (m.y.b.p.)



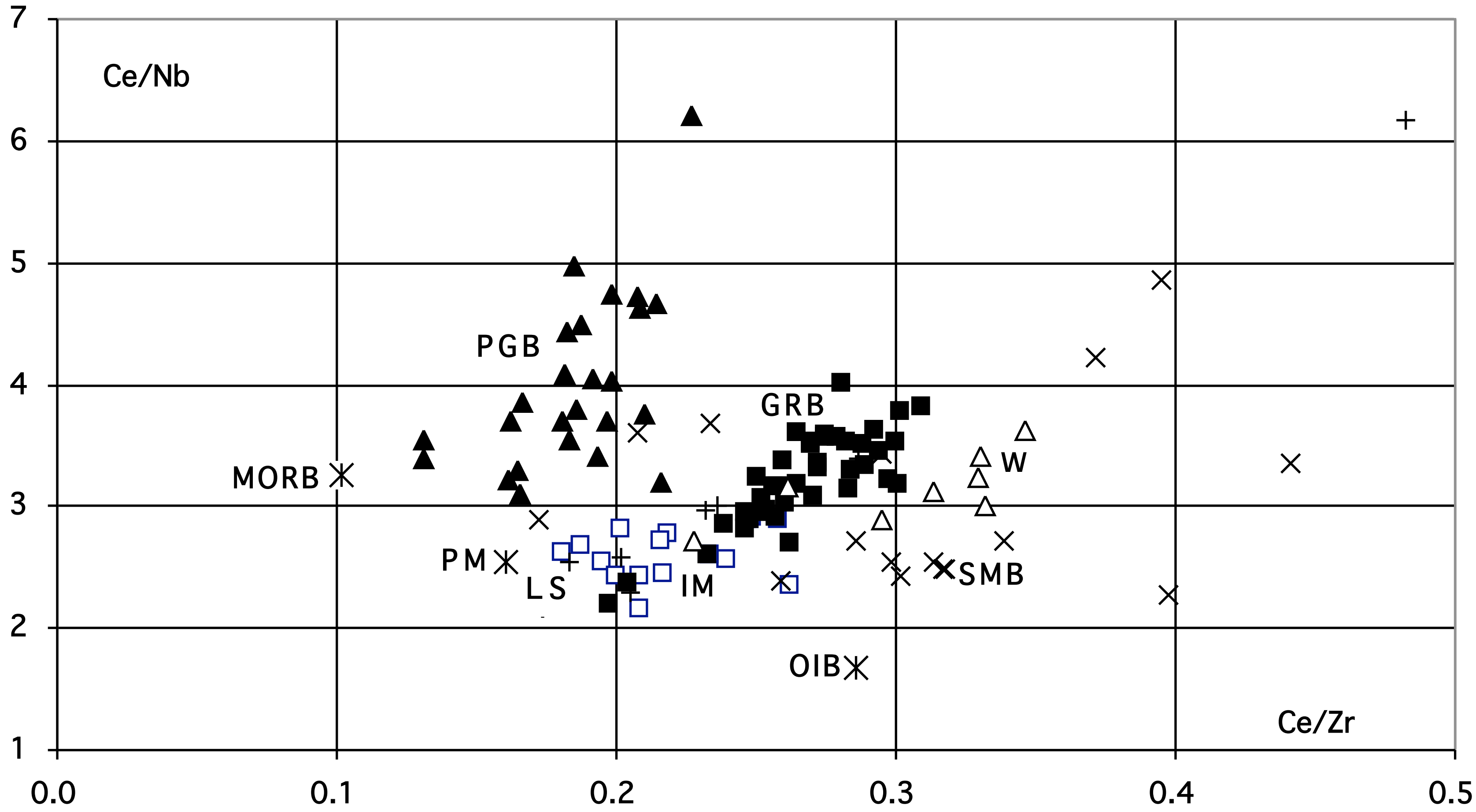
a
0
20km
a
b
b
VF
c
WSRP
Malheur River
Vale
d
c
a
b
a
MGG
OIG
Snake River
d
d
d
extensional duplex
b
0
20km
Wallula Gap
Wallula Gap
Wallula Gap Fault
Walla Walla Syncline
Washington
Oregon
c
Bond
Brothers
Newberry Volcano
20
0
20km

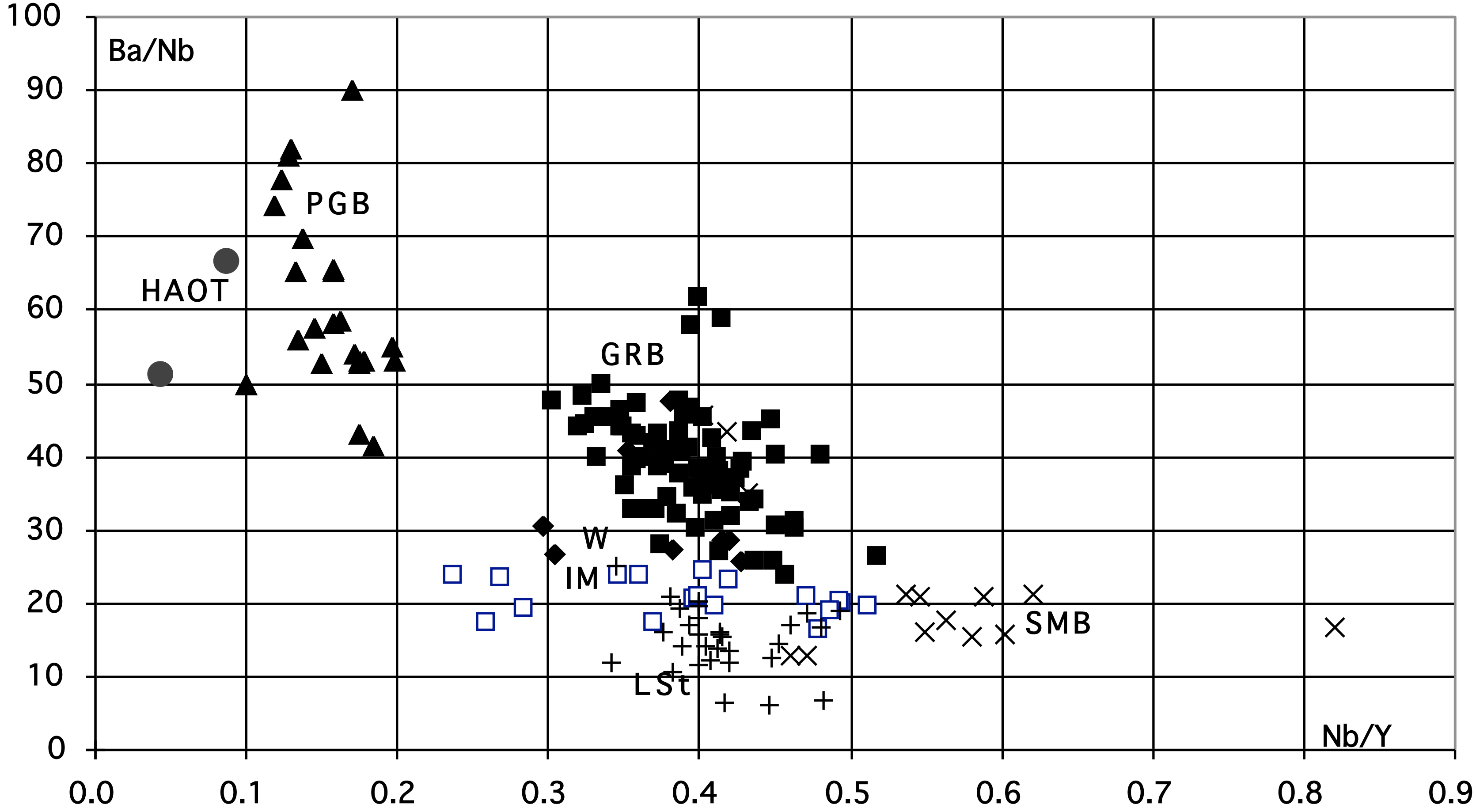


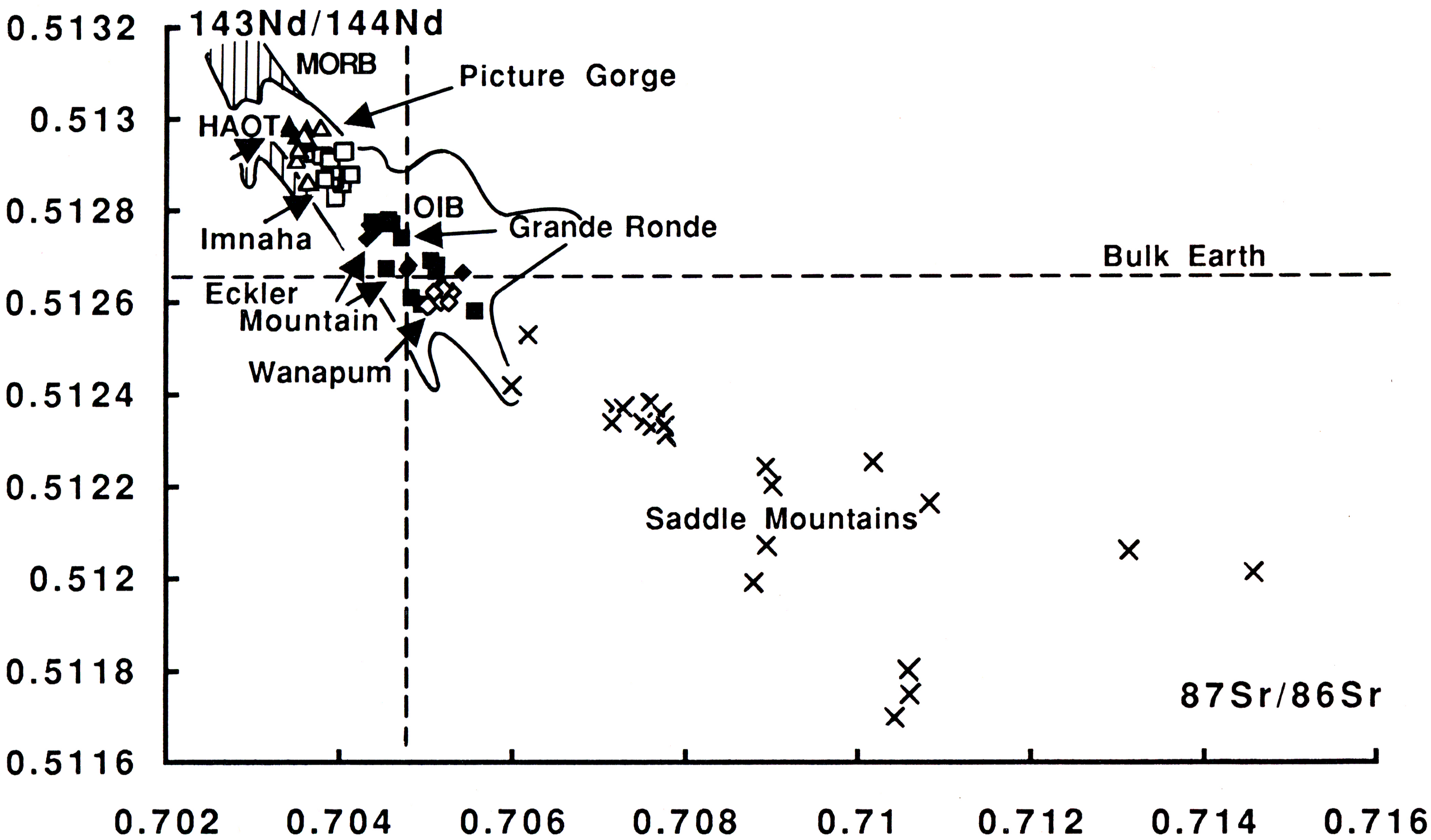
STEENS MOUNTAIN
MAP AREA: Middle and South forks of Malheur River
MALHEUR GORGE
SOUTHEAST COLUMBIA PLATEAU
SOUTH
NORTH
KOOL SPRING FORMATION
YOUNGER CALC-ALKALINE SEQUENCES
HUNTER CREEK
DINNER CREEK
GRANDE RONDE
BIRCH CREEK
UPPER STEENS
UPPER POLE CREEK
IMNAHA
VENATOR RANCH
LOWER STEENS
LOWER POLE CREEK
PRE-TERTIARY ACCRETED TERRANES
OLIGO-MIOCENE CALC-ALKALINE VOLCANICS

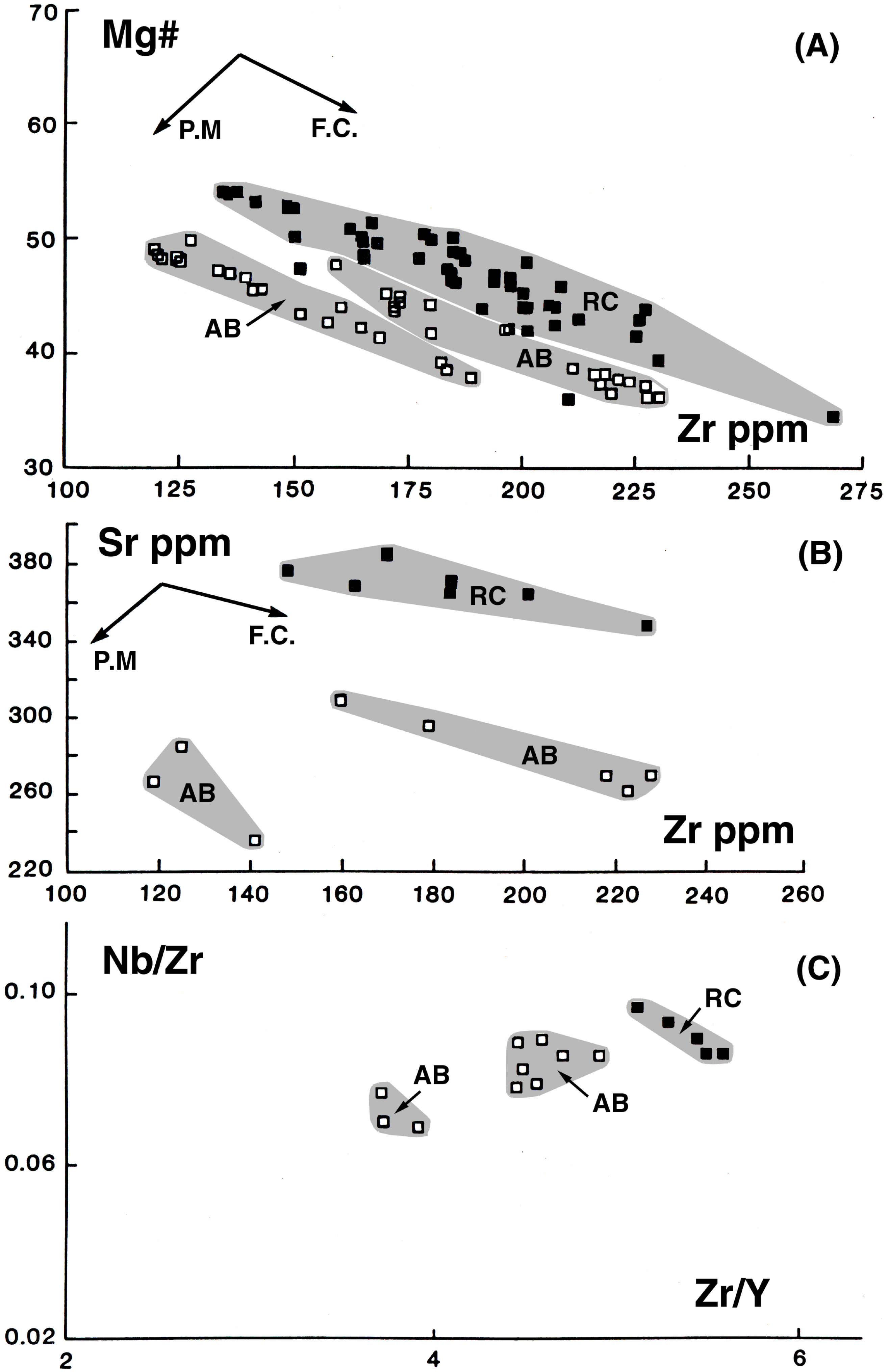


(a) Umatilla Member
70
60
50
40
30
20
10
0
metres
Umatilla
Sillusi
Umatilla
2.4
2.6
2.8
3.0
3.2
3.4
3.6
WT% TiO_2
0.8
2.6
1.0
1.1
1.2
1.3
1.4
1.6
WT% P_2O_5
(b) Cohassett Composite Flow
50
0
metres
AH
SC
SF
SC
AH
CC
1.7
1.8
1.9
2.0
2.1
WT% TiO_2
0
0.1
0.2
0.3
0.4
0.5
WT% P_2O_5


Ce/Nb
7
6
5
4
3
2
1
PGB
GRB
MORB
W
PM
LS
IM
SMB
OIB
Ce/Zr
0.0
0.1
0.2
0.3
0.4
0.5


Ba/Nb
Nb/Y
PGB
HAOT
GRB
W
IM
LSt
SMB
100
90
80
70
60
50
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


143Nd/144Nd
0.5132
0.513
0.5128
0.5126
0.5124
0.5122
0.512
0.5118
0.5116
MORB
Picture Gorge
HAOT
OIB
Grande Ronde
Imnaha
Bulk Earth
Eckler
Mountain
Wanapum
Saddle Mountains
87Sr/86Sr
0.702
0.704
0.706
0.708
0.71
0.712
0.714
0.716


Mg#
(A)
P.M
F.C.
AB
RC
AB
Zr ppm
70
60
50
40
30
100
125
150
175
200
225
250
275
Sr ppm
(B)
P.M
F.C.
RC
AB
AB
Zr ppm
380
340
300
260
220
100
120
140
160
180
200
220
240
260
Nb/Zr
(C)
RC
AB
AB
Zr/Y
0.10
0.06
0.02
2
4
6