Characterisation of Controls on Sediment Distribution and Correlation Lengths within Basaltic Provinces: Columbia River Basalts as an Analogue for the Faroe-Shetland Basin

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1. Introduction

The Columbia River Basalt Province (CRBP) is a Miocene Large Igneous Province (LIP) in the Northwest of the United States and covers a total area of about 163,700 km^2. The lava flows erupted from vent systems in North Oregon and South Washington and interacted with coeval fluvial, lacustrine, and marine environments. Today, the area offers excellent access to the intercalated stratigraphy of basalt and sedimentary interbeds, and is one of the best studied LIP's.

The purpose of this work is to reconstruct the response of the Miocene drainage system to the different phases of eruption of the LIP, This will expand understanding of factors that controlled the distribution of drainage systems, their morphology and architecture. This model will provide comparative data for inter-lava field prospects in the Faroe-Shetland Basin, allowing a more informed evaluation of reservoir potential in this play.

2. Geological Setting

The CRBP lies within an intermontane basin that is limited by the Cascade Range to the West, the Rocky Mountains to the East and the Blue Mountains to the South. The CRBP covers areas of of south Washington State, North Oregon and West Idaho and forms the Columbia Plateau (figure 1). The Columbia Plateau is formed by the Miocene-age Columbia River Basalt Group (CRBG), which erupted from vent systems located in the east and south of the plateau from *c*. 17 to 6 Ma. The basalt flows cover a total area of *c*. 163,700 km^2 with a total volume of *c*. 174,300 km^3 (Tolan

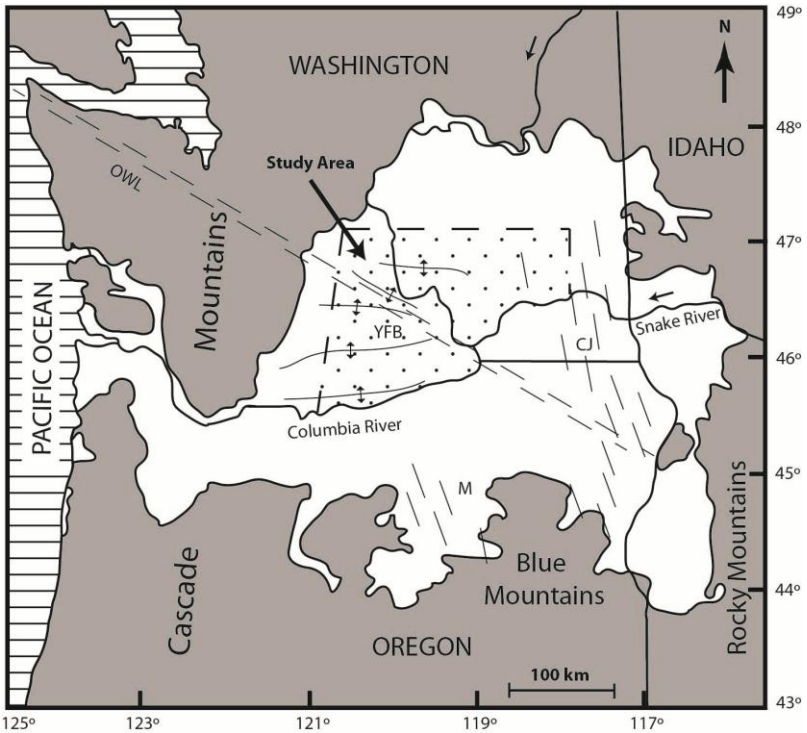

Figure 1: Geological setting of the Columbia River Basalt Province showing major tectonic and magmatic features and the study area. White field indicate areal extent of the Columbia River Basalt Group. CJ = Chief Joseph Dike Swarm, M= Monument Dike Swarm, OWL = Olympic-Wallowa Lineament, YFB = Yakima Fold Belt (modified after Reidel *et al*. 1989b, Tolan *et al*. 2009).

et al. 1989). The CRBG is formally divided into 5 formations: the Imnaha, Picture Gorge, Grande Ronde, Wanapum and Saddle Mountains Basalt in order of decreasing age. Based on field observation, geochemistry, palaeomagnetism and isotope dating the formations are further differentiated into 14 members and subsequently more than 300 single flows (Waters 1961, Nathan & Fruchter 1974, Schmincke *et al*. 1976b, Swanson *et al.* 1979, Reidel *et al*. 1994, Reidel *et al*. 1989). The basalt flows are locally interbedded with sedimentary successions of siliciclastic and volcaniclastic sediments, which were deposited within a fluvio-lacustrine to shallow marine environment. The interbeds in the western part are assigned to the Ellensburg Formation, those in the north western part of the Columbia Plateau to the Latah Formation (Swanson et al. 1979b). Due to the west-central location of the study area present, interbeds are formally assigned to the Ellensburg Formation. Due to their stratigraphic position this formation is subdivided into several members (figure 2). The Grande Ronde Basalt marks a phase of high eruption tempo and volumes

(figure 3). The Wanapum and Saddle Mountain basalts are characterised by waning volcanism.

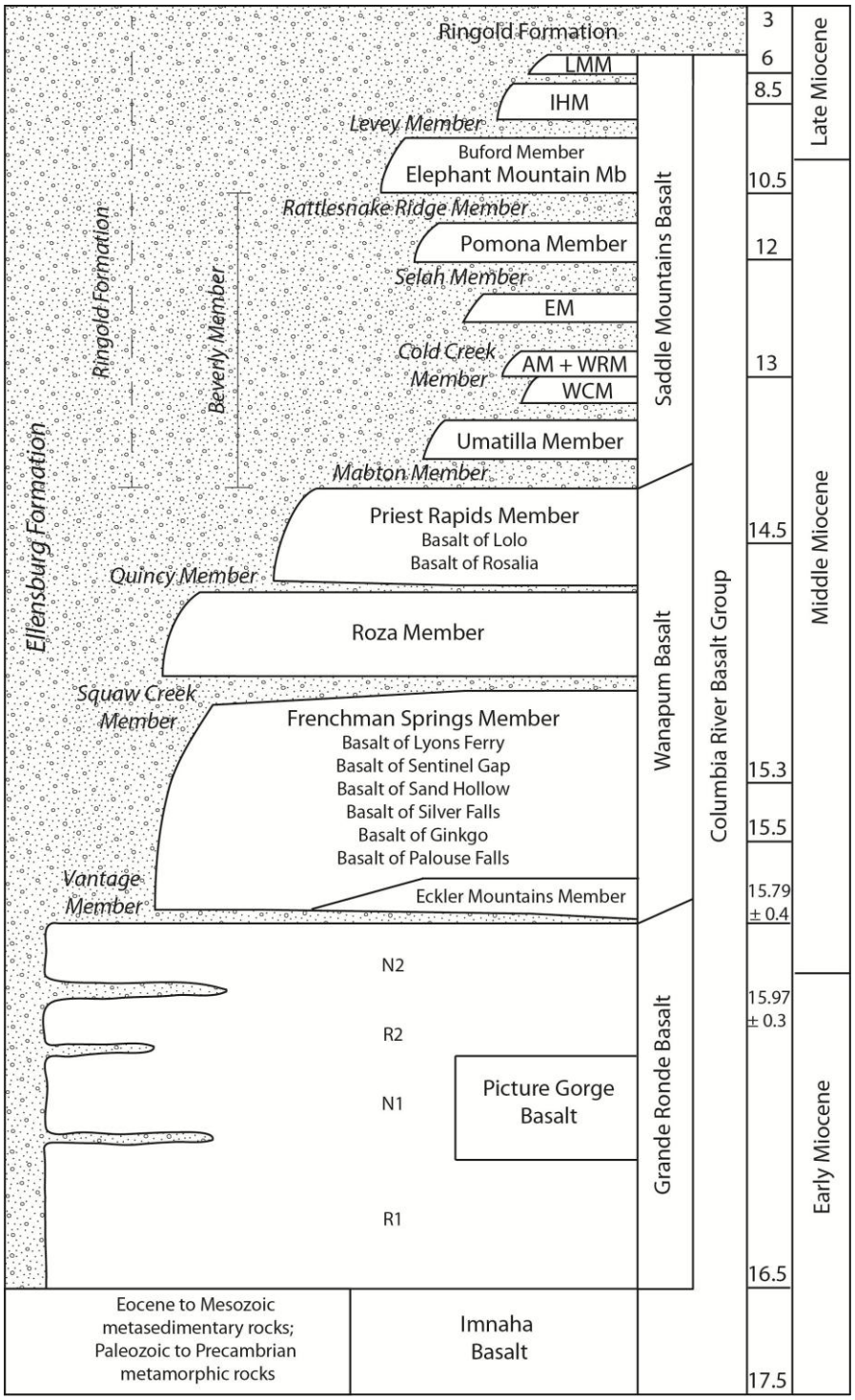

Figure 2: Stratigraphy of the Columbia River Basalt Group. AM = Asotin Member, EM = Esquatzel Member, IHM = Ice Harbour Member, LMM = Lower Monumental Member, WCM = Wilbur Creek Member, WRM = Weissenfels Member (modified after Smith *et al.* 1989, Reidel *et al*. 1989b, Tolan *et al*. 2002).

The CRBP is divided into 4 structural subprovinces: (1) the Yakima Fold Belt Subprovince in the western part, (2) the Palouse Subprovince located to the North, (3) the Blue Mountains Subprovince covering the southern plateau and extending into the central part, and (4) the Clearwater-Weiser Embayment, which is located along the eastern margin (Reidel *et al*. 1989b).

The tectonic and magmatic activity in the Columbia basin is associated with plate-margin tectonics between the Pacific and North American plate (Hooper *et al*. 2007, Reidel *et al*. 1989b, Smith 1992). Seismic data and borehole drilling record crystalline basement of the North American craton and Jurassic- to Eocene-aged continental sedimentary rocks of accreted continental terranes. Before the eruption of the CRBG the region had already undergone crustal rifting, subsidence and deposition of siliciclastic sediments and volcanic rocks (Catching & Mooney 1988, Reidel *et al*. 1994). Additionally, the region was influenced by clockwise rotation of crustal blocks of different amounts, probably initiated by extension of the Basin and Range area (Hooper & Conrey 1989, Magill *et al*. 1982, Reidel *et al*. 1984). Although the structural deformation of the lithosphere is linked to magma production, several hypotheses exist about the petrogenesis of the magmatism. Some authors assume mantle plume genesis within an extensional back-arc area (cf. Camp 1995, Catching & Mooney 1988, Hooper e*t al*. 1995, Hooper *et al*. 2002, Hooper *et al*. 2007). However, non-plume models consider back-arc spreading and / or back-arc convection leading to mantle upwelling and volcanic activity (cf. Baksi 1988, Smith 1992, Smith 2007, Wells *et al*. 1984).

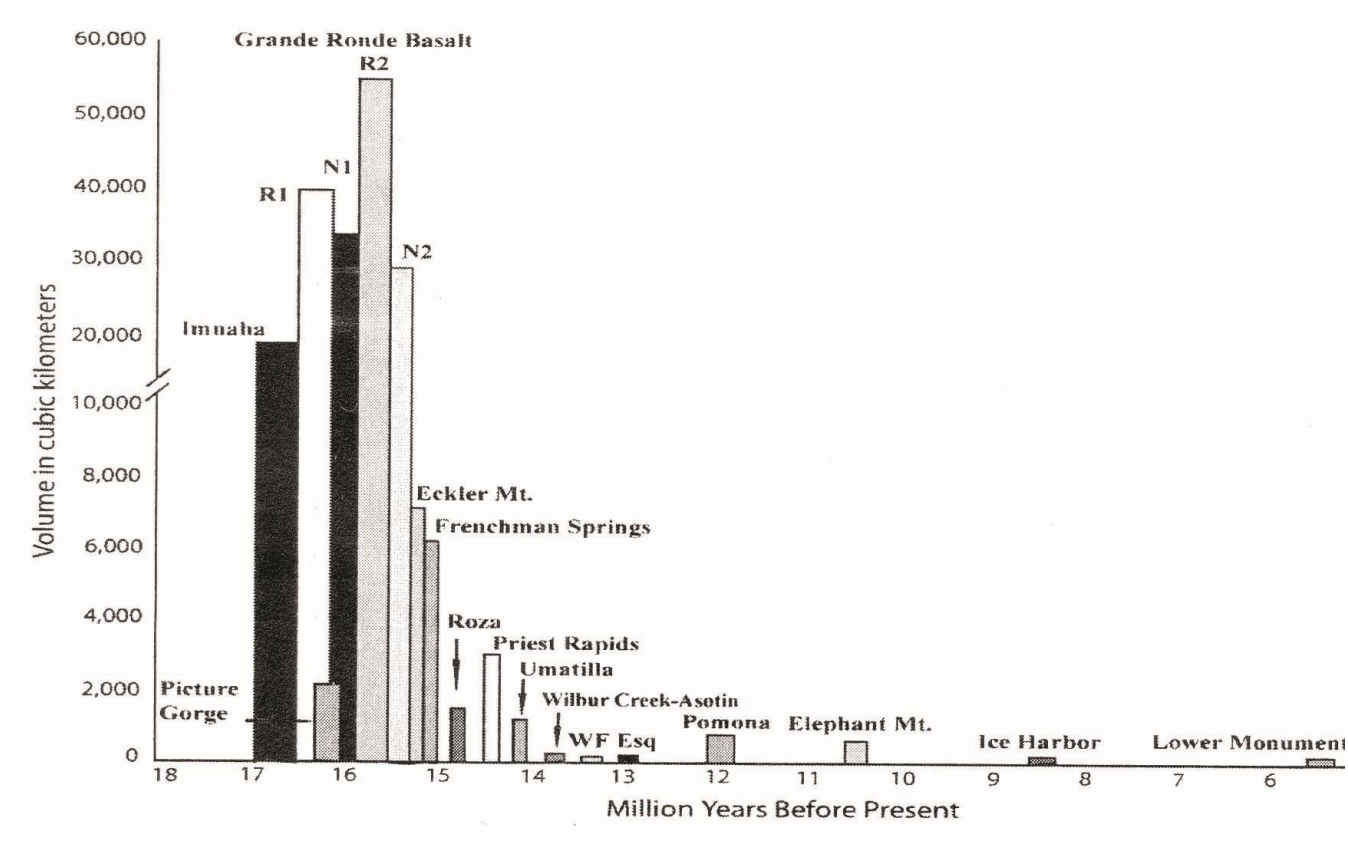

Figure 3: Eruption volumes of the Columbia River Basalt Group. Note change in scale for volume (modified after Tolan *et al*. 2009).

3. Material and Methods

The research project is based on a main field season in November 2010. The study area comprises the west-central part of the Columbia River Basalt Province (figure 4). In total, 14 locations of sedimentary interbeds were studied, and 29 sections were logged (in total *c*. 75 m). The codes, which are used in sedimentary logs are outlined below (table 1). The interpretation of sedimentary structures and depositional settings is based on the facies code in table 2.

Standard thin sections (50 samples) and 50 pollen slides were prepared in the Department for Geology and Petroleum Geology, University of Aberdeen. Palynology preparations were also made in the same laboratories using standard processing techniques.

The facies model is based on the location, stratigraphic position, lithology, depositional setting and paleocurrent data of sedimentary interbeds, and on the lateral extent of the basalt flows (after Tolan *et al*. 2009). Correlation of these data suggests 5 distinct evolutionary stages of the drainage system. This model will be outlined in detail below.

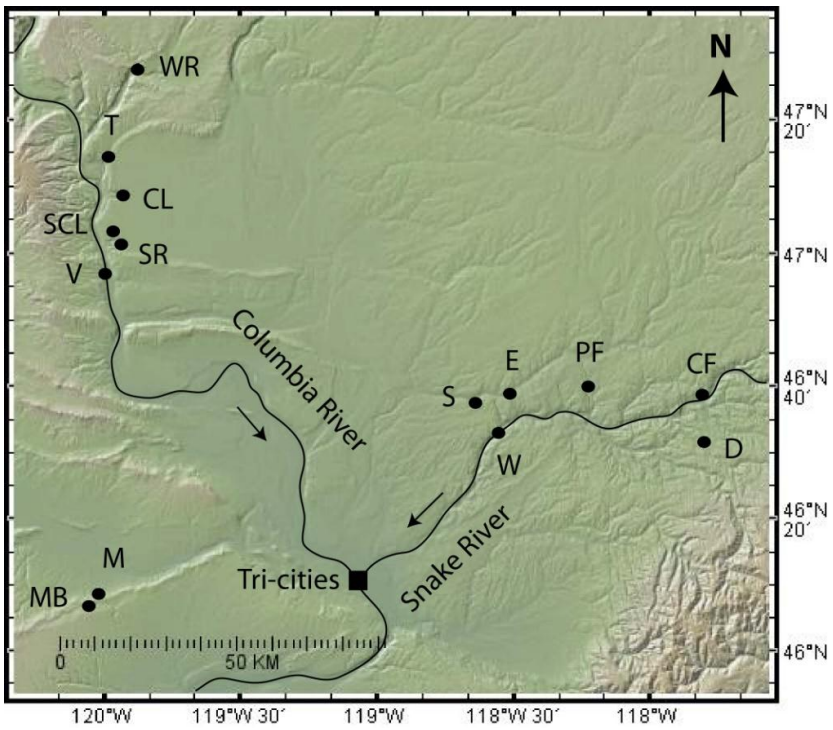

Figure 4: Map showing locations of exposed sedimentary interbeds (black dots), with letters indicating outcrop labels.

Table 1: Symbols used in sedimentary logs.

Mudstone	Conglomerate	Pyroclastics
Siltstone, parallel laminated	Breccia, clast-supported	Scoria
Silstone, cross-laminated	Breccia, matrix-supported	Basalt, colonnades
Sandstone, massive	Diatomite	Basalt, thin sheets
Sandstone, parallel bedded / laminated	Coal	Basalt, brecciated
Sandstone, cross-laminated	Peat	Pillow basalt
Sandstone, cross-bedded	Chert	Layers of rounded gravel
Sandstone, gravelly cross-bedded	Palaeosol	Layers of angular gravel
Fluvial channel	Reworked by fluvial or mass flows	Lacustrine offshore
Fluvial overbank	Paleosol	Lacustrine nearshore
Siliceous offshore	Primary Pyroclasts	Lacustrine delta
Siliceous nearshore	Reworked Pyroclasts	Lacustrine swamp
Lense-like beds	Fossil leaves	gr Granules
Load structures	Fossil wood debris	pe Pebbles
Flute casts	Foosil rootlets	co Cobbles
Flame structures	cl Clay	bo Boulders
Slumping	si Silt	
Climbing ripples	f Fine-grained sand	
Accretionary lapilli	m Medium-grained sand	
Burrow traces	c Coarse-grained sand	

Table 2: Facies scheme for alluvial and lacustrine sediments, and palaeosol horizons.

Lithofacies	*Description*	*Interpretation*
1. Mudstone		
Siliciclastic	Sheets or lenticular beds of massive to paraellel laminated siliciclastic brown to grey clay and silt, intercalated with peat or coal layers, may be rich in fossil plant debris and rootlets.	*Fluvial:* Deposition from suspension after sheet flows in fluvial overbank facies, preservation of organic-rich matter resulting in intercalated peat or coal layers. *Lacustrine:* Distal facies of deposition from suspension within standing water bodies, peaty layers suggest swamp facies.
Diatomaceous	Sheets or lenticular beds of massive to parallel laminated light grey to yellowish mixed siliciclastic-diatomaceous clay and silt.	Deposition of diatomaceous material from suspension within standing fresh water bodies of relative high nutrient and light conditions and increased siliciclastic input.
2. Sandstone		
Cross-laminated sandstone	Lenticular Beds of planar or trough cross-laminated fine- to medium-grained sandstone, trough set height <4 cm; creamy, light brown or grey-coloured, contains ichnofacies locally.	Result of migrating sinuous- to straight crested ripples in realtively weak currents, common towards the top of sany bedforms like dunes, point bars, plane beds. Climbing ripple lamination records high rates of sediment accumulation and flow velocity.
Cross-bedded (pebbly) sandstone	Lenticular beds of tabular or trough cross-bedded medium- to coarse-grained (gravelly to pebbly) sandstone, trough set height >4 cm; creamy, light brown or grey-coloured, contains ichnofacies locally.	Tabular sets of cross-beds record migration of straight-crested dunes. Trough sets gets formed by migrating sinuous-crested dunes. Pebbly layers often at erosional surfaces of channel bases, bars or dunes.
Planar bedded sandstone	Lenticular beds of horizontally bedded fine- to coarse-grained sandstone, contains locally rootlets and fossil plant debris, pebbly in places, contains ichnofacies locally.	Planar beds of sand may occur at any level in the channel, but tend to more common towards the top as the result of plane bed transport in a lower flow regime. Micaceous fine- to medium-grained sand commonly referred to plane beds deposited during the upper flow regime.
Massive (pebbly) sandstone	Beds of structureless, pebbly fine- to coarse-grained sandstones, may contain ichnofacies locally.	Commonly record of slumping and sliding of bank cuts or over steepended bar fore sets. Sedimentary structures may also be destroyed by surface weathering or bioturbation.
3. Conglomerate		
Cross-stratified	Lenticular beds of mono- or polymictic pebble- to cobble conglomerate, predominantly matrix-supported, sandy matrix, imbrication, interbedded with thin sand-rich units.	Deposition of bed load on the downstream end or lateral of migrating fluvial gravel bars, commonly interbedded with the sandstone subfacies and massive or horizontally bedded conglomerates.

Horizontally bedded	Sheet-like beds of planar bedded or low-angle stratified conglomerates. Texture and composition equivalent to the cross-stratified conglomerate subfacies.	Deposition within in-channel gravel sheets, or at the initial phase of gravel bar deposition during or immediately after floods. Clast pavements common between longitudinal bars due to increase in flow stage.
Massive	Sheets or lenticular beds of structureless, less sorted predominantly matrix-supported pebble conglomerate, appears as polymictic or monomictic conglomerate.	Deposition of bed load as fluvial gravel lags on channel floors or on top of braid bars, conglomerates of intraformational clasts often associated with erosional surfaces related to channel migration or crveasse splays, when overbank material gets eroded and reworked.
4. Breccia	Sheeted thin beds of unsorted pebble monomictic breccia, matrix-supported predominanly.	Small-scale fan delta deposition as a result of landslides or debris flows entering a water standing body or a river. Layers of larger intraformational clasts are the result of sliding or falling from the cut bank.
5. Tuff		
Primary pyroclasts	Massive or horizontally bedded or laminated tuff, composed of fine- to coarse grained felsic (or rarely basaltic) ash.	Deposition of vitric ash from pyroclastic fall out processes related to explosive volcanism.
Reworked pyroclasts	Massive, horizontally or cross-laminated of fine- to coarse tuff, composed of felsic or basaltic ash.	Pyroclats are reworked syn-eruptively by falling into a standing fresh water body (resedimented syn-eruptive mudstone and sandstone)
6. Diatomite	Massive beds of white to yellowish diatomite, associated with chert lenses, locally interbedded with mud-rich sediments.	Settling of diatoms and diatomaceous material from suspension within standing water bodies of high nutrient level and limited input of siliciclastic material.
7. Paleosol		
Vertisol	Horizons of grey-brownish clay- and mudstone, shrinkage features are 1-3 cm wide, and up to *c.* 12 cm long, often graded boundaries to adjacent sedimentary units.	Soil formation from clay-rich sediments or basic rocks. Vertisols are rich in smectite or montmorillonite (<30%) and characterised by shrinkage cracks and slickenslides as a result of alternating swelling and shrinking during periods of wet and dry seasons. Vertisols are common seasonally humid or temperate climates.
Ferralsol	Red horizons of deeply brecciated basalt, which locally grades into mud- and organic-rich structureless beds (saprolite).	Soil formation from deeply weathered basalt units by desilification and enrichment of Al- and Fe-oxides (hematite, goethite, maghemite) in the Bu horizon. Main clay mineral is caolinite. The less evolved horizon below the Bu horizon is commonly referred to saprolite. Ferralsols are common in the humid tropics and subtropics.

4. Characterisation of Sedimentary Interbeds

The reconstruction of the Miocene drainage system is based on field observations and sedimentary sections from interbeds of the Grande Ronde basalt, Vantage, Squaw Creek, Quincy,, Selah and Rattlesnake Ridge Member. The characteristics of each location in terms of lithofacies, sedimentary structures and depositional setting is outlined below and summarised in table 3.

4.1. Grande Ronde (R_2-N_2 contact)

Wagon Road (WR)Locality

This location comprises three sections, each of which is 5.0 – 6.0 m thick and consists predominantly of intercalated beds of planar-laminated mudstone (0.5 – 10 cm thick) and cross-laminated siltstone (1.0 – 15.0 cm thick). Additionally, these units are interbedded with channel- and sheet-like bodies of trough cross-laminated and massive fine- to medium-grained sandstone. The averaged thickness of individual beds is 0.8 – 15.0 cm, or 10.0 – 80.0 cm, respectively (figure 5). The fine-grained sandstones are further characterised by occasional climbing ripple cross-lamination. The composition of the mud-, silt- and sandstones is generally volcaniclastic and rich in mica. The interbed includes lenticular beds of 25.0 – 30.0 cm thick matrix-supported conglomeratic breccias, which mainly are composed of angular- to subrounded granule- to small pebble-sized basalt grains. The internal structure shows inclined stratification.

At the north western end of the outcrop, the base of the interbed is intercalated with basaltic breccia, whereas the upper N_2 basalt is a fine-grained pyroxene bearing flow that slightly invades the interbed. The contact with the upper basalt flow has not been seen; however, the basalt is visible at this outcrop and was found a few metres on top of the sections.

Interpretation

The sedimentary succession represents a fluvial environment, which is dominated by floodplain and subsequent crevasse splay deposition composed of mud-, silt- and fine-grained sandstone. This facies is incised by sandy and gravel-rich ribbons, which are interpreted as minor channels filled by sandy bedforms like dunes, ripples, lower stage plane beds and gravelly bedforms including fine-grained bars. Additionally, point bar deposition was noticed in other parts of the interbeds, suggesting a meandering character for the fluvial system. The basaltic breccia, which occurs within the lower part of the interbed, represents reworked material of a local spatter cone deposition. The spatter cone deposits grade into a sand-rich body, which forms a gravel bar.

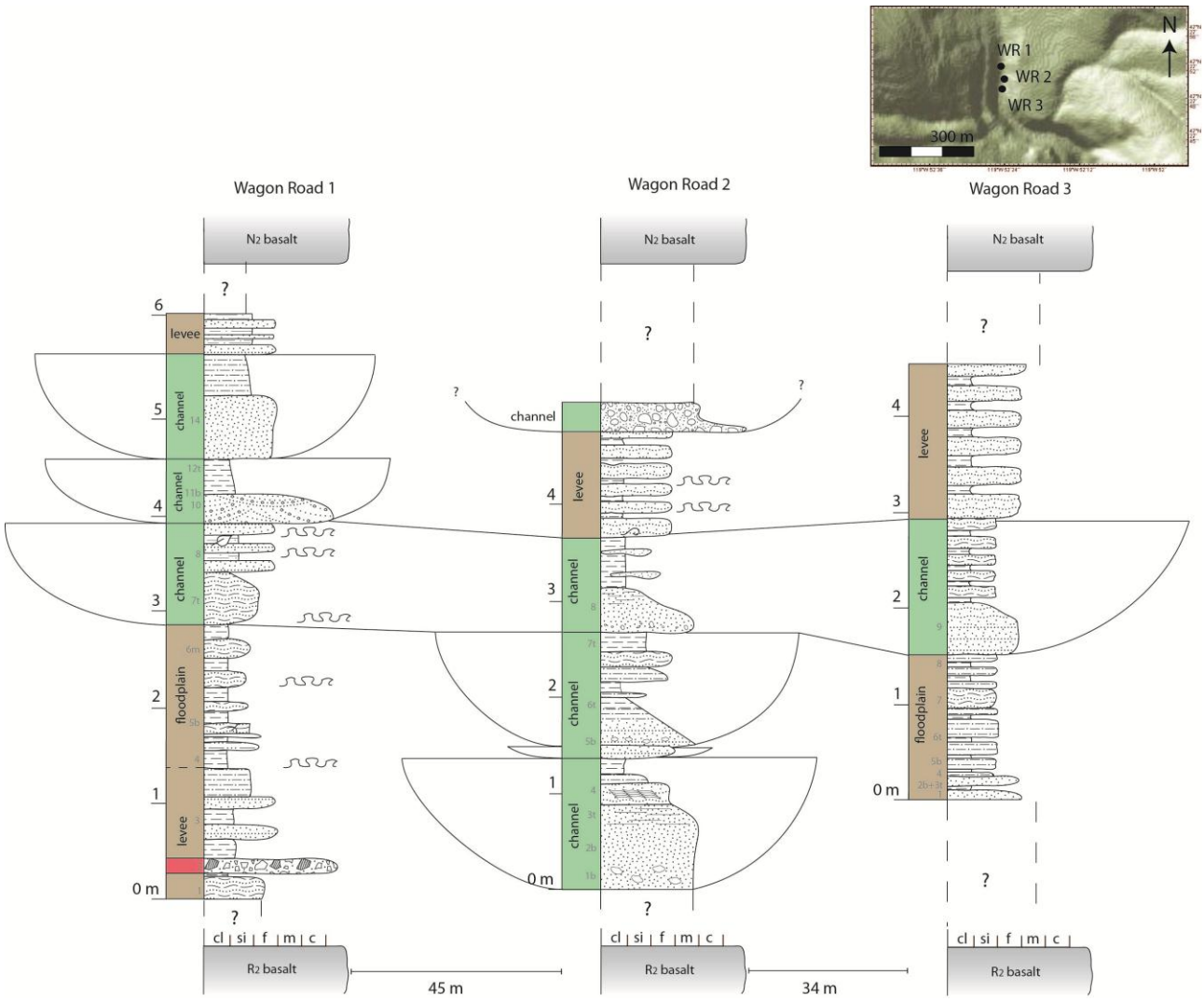

Figure 5: Correlation of sedimentary sections of the Wagon Road locality (Grande Ronde time). Interbed is dominated by a fine-grained fluvial overbank facies and intercalated with crevasse splay and channel deposits.

4.2. Vantage Member

Central Ferry (CF) Locality

Central Ferry represents the flow top of the Grande Ronde basalt, which is characterised by a blocky dark grey flow top grading upsection into a strongly weathered and brecciated red horizon over *c*. 3.3 m (figure 6). The clasts of this breccia consist of red-coloured, aphyric, vesicular basalt and vary from angular granule to boulder size. Cavities in the basalt are filled with green-coloured mud and give the horizon a mottled character. The texture is homogeneous, but the colour changes red to brown-grey at the top. The overlying Frenchman Springs flow is composed of massive and dark grey, slightly columnar basalt. The contact with the Frenchman Springs Member is sharp and flat.

Interpretation

The structure and lithology of the red horizon suggest intense weathering of a flow top during a long period of quiescence between the emplacement of two lava flows. The horizon is regarded as

an early stage of ferrosol formation (for more details see Windust locality, Vantage Member).

Dodge (D) Locality

The Dodge locality is characterised by a pale, brecciated mud-rich contact channel-like bed between the Grande Ronde and the Frenchman Springs or Eckler Mountain Member (thickness *c*. 3.0 m). The Grande Ronde flow is a massive, aphyric and fine crystalline basalt, while the top basalt is characterised by small feldspar and pyroxene crystals and vesicular habitat with a sharp contact to the underlying interbed (figure 6). At the base, the interbed is composed of a *c*. 1.3 m thick pale clast-supported basalt breccia with granule to pebble-sized clasts sitting in a muddy to sandy matrix. The middle part of the section is characterised by a *c*. 1.0 m thick light brown, gravelly basalt breccia with a muddy matrix that contains fossil plant debris. The upper part is marked by rather reddish gravel-sized breccia with a thin (1.0 – 3.0 cm) dark-coloured mudstone layer on top. Each of the described units has sharp contacts mainly represented by the change of colour. The texture is chaotic and clast- to matrix-supported. The section in general is much consolidated and the basalt clasts are intensively altered.

Interpretation

The composition and textures of this locality suggest deposition of reworked basaltic material by stream flows within a small valley. The basalt clasts were probably eroded from flanks of nearby lava flows. The textures indicate an immature, proximal small fluvial channel.

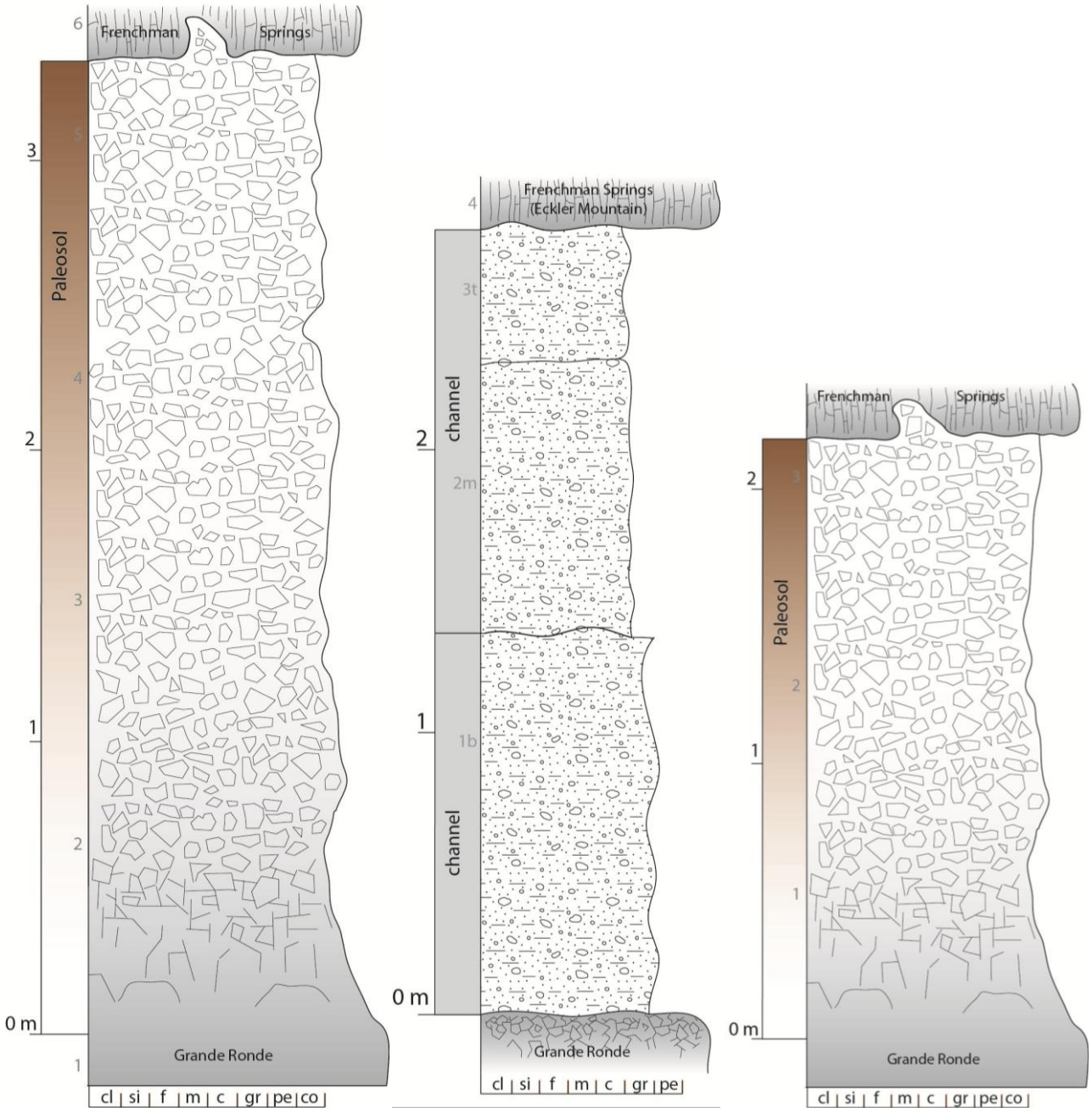

Figure 6: Logs of sedimentary interbeds at Central Ferry (left), Dodge (middle) and Estes (right, Vantage Member). Central Ferry and Estes represent red basalt contacts, while Dodge indicate deposition from fluvial(?) or mass flows.

Estes (E)Locality

Estes represents a reddish horizon of *c*. 1.8 m thickness between the Grande Ronde and Frenchman Springs Basalt. This horizon consists of an unsorted, clast-supported basalt breccia, which grades from the underlying blocky basalt. The clast size of the breccia ranges from granules to boulders. The matrix is a grey to reddish muddy to silty sandstone. To the northeast, the interbed becomes slightly horizontally bedded (figure 6).

Interpretation

This locality is considered as the weathered and brecciated flow top of the Grande Ronde Basalt, and represents the early stage of ferrosol formation (see also Windust locality, Vantage Member).

Palouse Falls (PF)Locality

Palouse Falls includes one interbed, which is represented by three sections, which range in thickness from *c*. 0.4 to 0.6 m. The interbed commences with a basal bed of grey to brown-coloured diatomaceous massive siltstone, which contains fossil wood debris and may be intercalated with thin layers of coal (2 – 15 cm thick). In section 2, this unit is covered by a 9.0 cm thick layer of coarse-grained massive arkosic sandstone, which is characterised by very angular to subangular basal basalt granules. The uppermost unit is dominated by a bed of light brown to light grey siliciclastic and diatomaceous mudstone (6.0 – 29.0 cm in thickness). This mudstone includes thin bedding to lamination and contains fossil wood fragments and varying proportions of volcaniclastic material (figure 7). The interbed lies between the rubbly flow top of the Museum Basalt (Sentinel Bluffs Member, N_2 Grande Ronde Basalt) and the massive jointed Palouse Falls flow of the Frenchman Springs Member. The contact between the upper basalt and the interbed is mostly sharp, but large invasive structures were also noticed.

Interpretation

The lithology of this interbed suggests deposition within a shallow lake or wetland. Coal beds or beds with a high amount of fossil plant debris are interpreted as lacustrine swamp facies, while silt-rich layers indicate nearshore facies. The interlayer of coarse-grained sandstone in section 2 implies deposition of a small incoming fluvial channel within a delta. The general sharp contact between the sediment and the thick basalt colonnades suggests that the water body was situated within a local basin, and was mostly dried out before the Palouse Falls flow entered the basin.

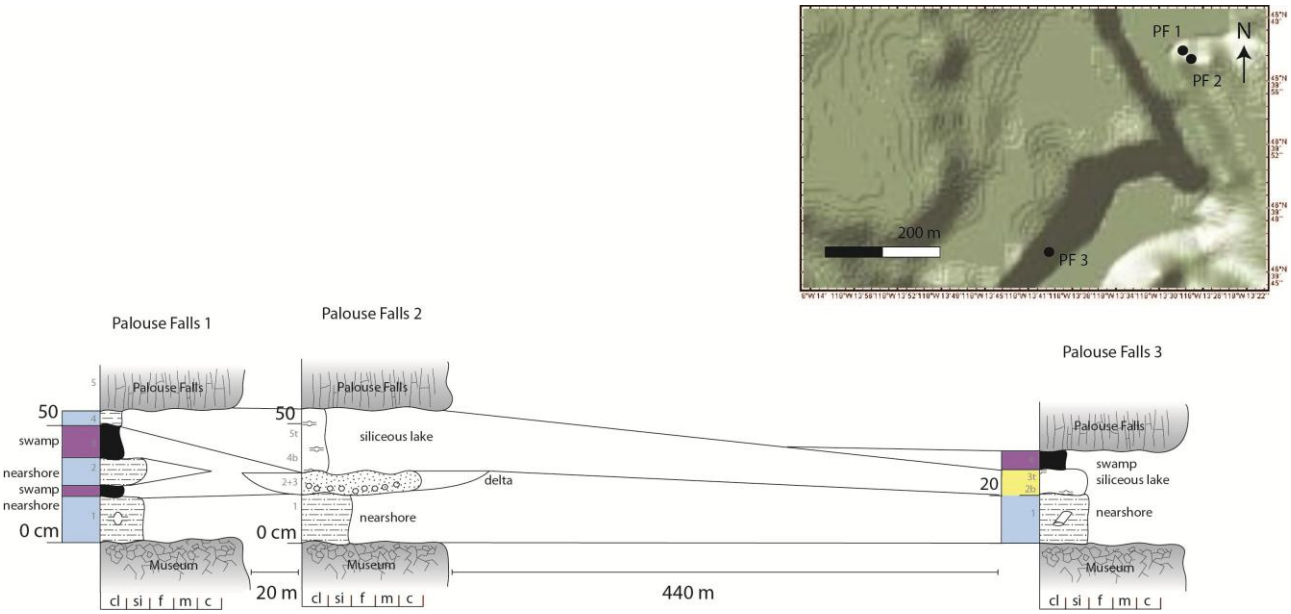

Figure 7: Correlation of sedimentary sections of the Palouse Falls locality (Vantage Member). Interbed represents deposition within a shallow lake or wetland.

Vantage (V) Locality

The Vantage locality includes 2 logged sections of *c*. 4.0 m each. Both are characterised by up to *c*. 80.0 cm thick units of mud-, silt- and fine-grained sandstone. These units are further characterised by fossil plant debris including leaves, roots and branches. The sandstones shows grading (section 2), but bedding is weak. The middle part of both sections is dominated by (trough) cross-bedded and minor massive fine- to coarse-grained sandstone, which contains layers and random granules and pebbles of pumice. The pumice clasts are well rounded. The cross-bedded sandstone bodies are normal and inverse graded and have erosive contacts (figure 8). The lower basalt flow is not exposed, but the interbed underlies a pillow-palagonite complex of the Ginkgo flow.

Interpretation

The interbed suggests sedimentation within a fluvial channel and overbank facies, including sandy to fine-grained bar, levee and more distal floodplain deposition. Section 1 includes the deposition of two superimposed bars, of which the lower one is reversed graded, and the upper one normal graded. The bars can be distinguished by a thin interbed of silty fine-grained sandstone, which is interpreted as the result of sedimentation within a cross-bar channel or chute channel. The lower bar deposition might be the upstream part, while the upper next bar deposition is possibly related to the downstream part (cf. Bridge & Tye 2000). The pumice clasts were presumably delivered from the Cascades.

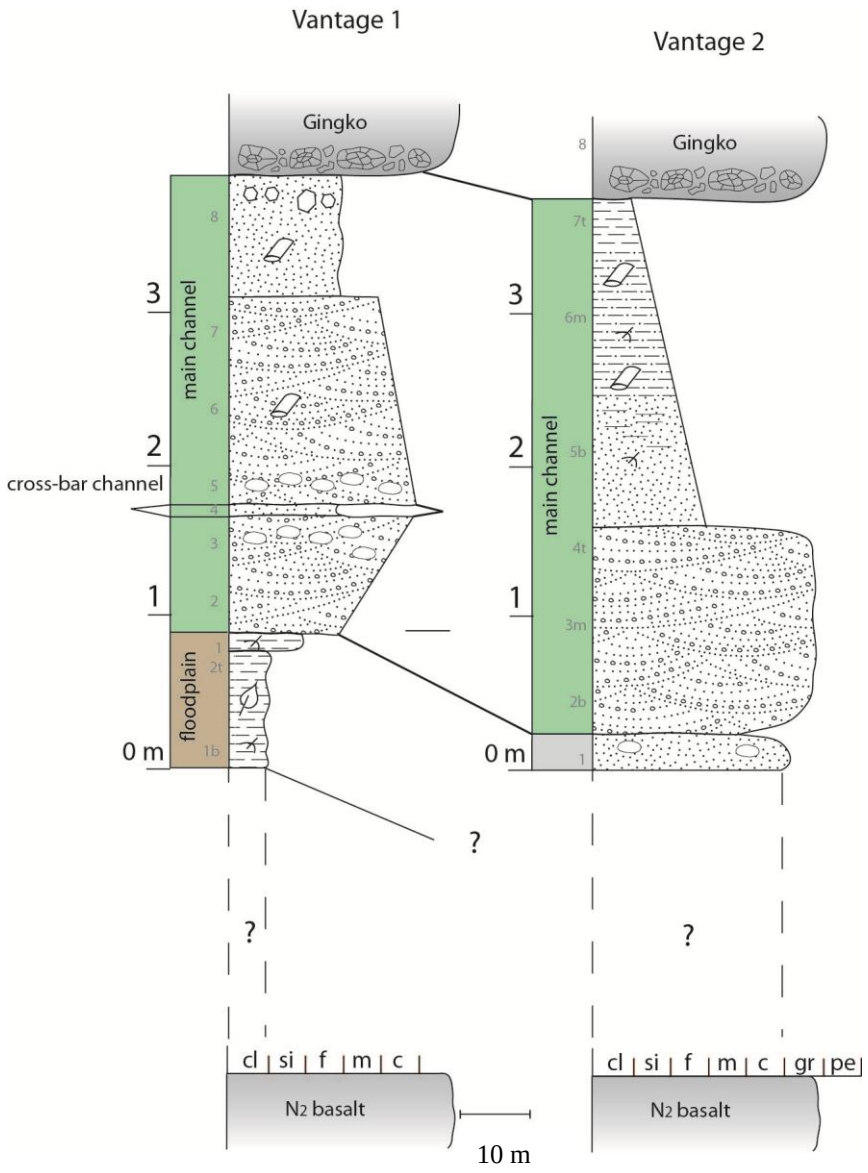

Figure 8: Correlation of sedimentary logs of the Vantage locality (Vantage Member). Deposition indicates pumice-rich fluvial channel and overbank facies.

Windust (W)Locality

The Windust location is characterised by a *c*. 1.5 m thick red horizon, which is situated between the lower N_2 Grande Ronde and the upper Frenchman Springs Member (figure 9). The flow top of the Grande Ronde Basalt is significantly brecciated and weathered and grades vertically into a silty, less brecciated reddish mudstone. The basalt clasts of the lower brecciated unit are of pebble- to boulder-size, and of angular shape. The fractures are filled with reddish mud, silt and angular basalt granules. The mudstone within the upper layers is characterised by a structureless texture and contains fossil plant debris (seeds). The mud-rich top has a maximum thickness of 50.0 cm and pinches out over 10's of metres.

Interpretation

The lithology and texture of the Windust interbed suggests soil formation of a ferrosol (saprolite) on top of the Grande Ronde Basalt. Typically, ferrosols (or oxisols) are deeply weathered soils of the humid tropics and subtropics and are characterised by red- or yellow-coloured Bu horizons enriched of Fe- and Al-oxides (hematite, goethite and maghemite). The main clay mineral is kaolinite. Ferrosols are common in humid forest soils with silica- or carbonate-rich substrate. Associated with relatively high temperatures and humid conditions is the process of desilification, which leads to the residue of Fe- and Al-oxides. The layer below the Bu horizon is commonly referred to saprolite (Scheffer & Schachtschabel 2002). This locality correlates with Central Ferry, Dodge and Estes, which indicate either similar (Dodge) or less (Central Ferry and Estes) evolved soil horizons. The palaeosol formation is probably related to local topographic highs within the Columbia Plateau, where the basalt flow top was subject to significant physical and chemical weathering. The palaeosoils are situated in the proximal to the eruptive fissures, and suggest relatively long-lasting periods of quiescence during the Vantage Member time.

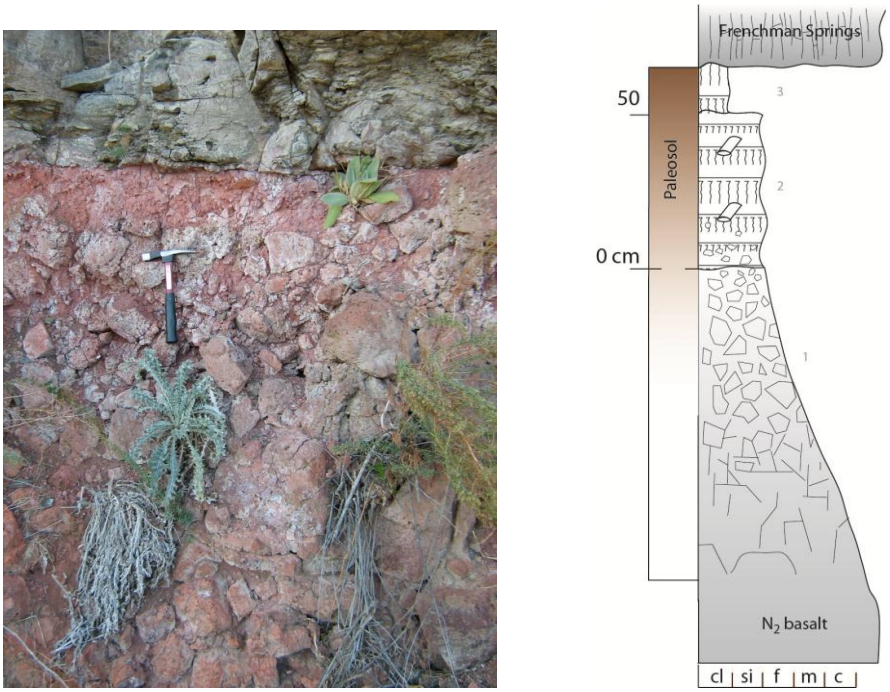

Figure 9: Paleosol formation (Saprolite) at Windust, section 1 represents typical horizons of soil formation.

4.3. Squaw Creek-Quincy Member

Caliche Lakes (CL) Locality

Caliche Lakes includes four sections, which range in thickness from *c*. 1.0 to 4.5 m. Sections 1 to 3 are characterised by a basal layer of basalt scoria (*c*. 3.6 m), which contains altered light grey- to yellow-coloured palagonite (degraded basaltic glass) and fragmented, scoriaceous basalt bombs and lapilli (figure 10). At the north eastern end of the road cut the scoria grades into diatomite (figure 11, section 4). The breccia underlies a 15.0 – 32.0 cm thick tuff unit, which shows horizontal bedding with individual beds of 5.0 – 15.0 cm thickness. The tuff further contains randomly scattered angular small pebbles of basalt and pumice. The interbed is covered by pillow basalt of the Priest Rapids Member.

Interpretation

The composition and textures of this interbed suggests spatter cone deposition of a proximal basaltic eruption. The erupted material felt into or next to a siliceous lake as indicated by the transition into a diatomite facies (section 4). The erupted basaltic bombs and scoriaceous material probably mixed up with the diatomaceous sediment they were erupting through and built up a spatter cone with an inclined stratification dipping away from the vent. The tuff layer on top of the scoria represents waning eruptive activity prior to the eruption of the Priest Rapids Basalt. Hence, the scoria eruption was time equivalent to the Squaw Creek or the Quincy Member. This locality has been described as a peperite generated by the invasion of the Roza flow into wet sediment (Schmincke 1967a, Carson 1987), however, the presence of lava bombs and inclined strata suggests scoriaceous deposition.

Figure 10: Basalt scoria at Caliche Lakes, covered by a thin light grey layer of tuffaceous sediment.

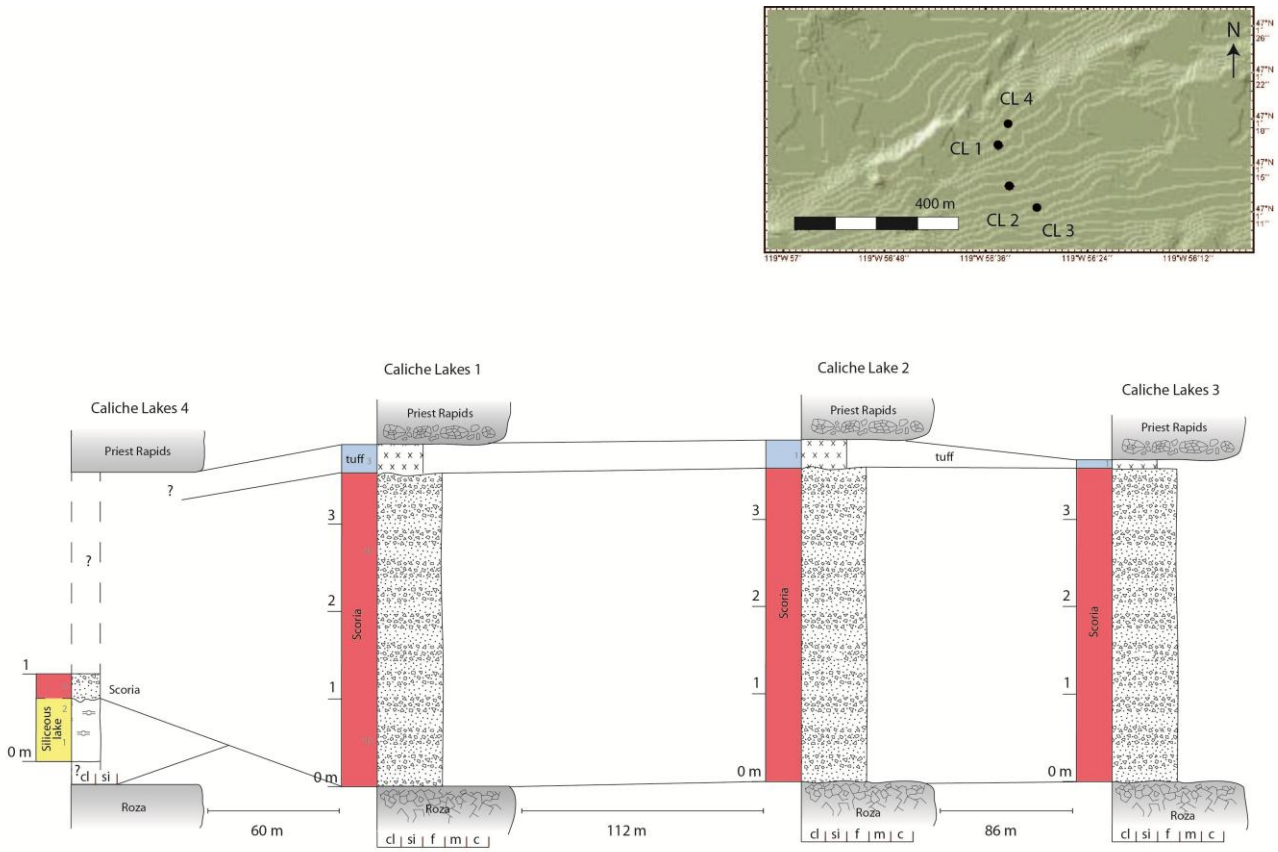

Figure 11: Sedimentary sections of the Caliche Lakes locality (Squaw Creek Member). Sedimentation took place within a siliceous lake setting. Section 4 shows non-peperitic diatomite and indicates distal part of the sediment-lava interaction.

Sulphur (S)Locality

Sulphur comprises one section, which constitutes a thickness of *c*. 0.4 m and is situated between the Roza (massive flow top) and Priest Rapids members, which is marked by a rubbly to slightly pillowed flow bottom including small spiracles. The interbed is composed of a volcaniclastic-siliciclastic succession of basal grey-coloured massive siltstone (*c*. 23.0 cm in thickness), which contains angular-shaped granules of basalt and mudstone. This unit is overlain by a 15.0 cm thick bed of light-brown wavey- to parallel-laminated siltstone. The top layer is dominated by a 5.0 cm thick layer of grey massive siltstone (figure 12).

Interpretation

This interbed is the result of lacustrine sedimentation that took place within a shallow lake or wetland. Due to the composition, this environment was connected to a fluvial system. The Priest Rapids contact suggests water-saturated conditions during the emplacement.

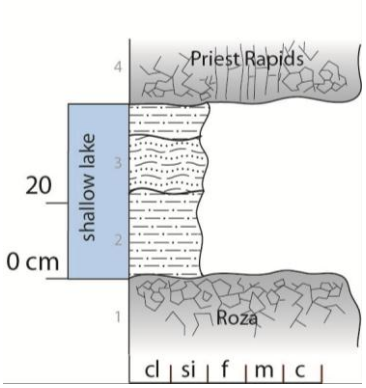

Figure 12: Sedimentary log of Sulphur (Squaw Creek-Quincy Member). Interbed indicates shallow lacustrine deposition.

Silica Road (SR)Locality

Silica Road includes one interbed, which is situated between the Frenchman Springs and the Roza Member. The interbed is represented by four sections, which range in thickness between 2.5 and 4.0 m. All sections are composed of diatomite, which contains chert nodules (silicified wood) or irregular chert lenses (figure 13 and 14). The upper part of the interbed may also contain thin layers of coal (a few centimetres in thickness) and 22.0 – *c*. 50.0 cm thick beds of siliciclastic and diatomaceous siltstone. The amount of siliciclastic material may increase continuously. Additionally, the diatomite is intercalated with the Roza flow in some parts. The contact between the interbed and the Roza basalt is sharp and flat in many places, but spiracles (*c*. 2.0 m in height, up to 1.0 m in width), invasive structures and areas of pillow basalt may also occur. The diatomite is slightly altered and indurated at the lava contact. The base of the interbed is not exposed.

Interpretation

The sediment lithology suggests lacustrine deposition within a siliceous lake. Siliciclastic input was limited, but increased slightly towards the end of the deposition. Most chert nodules are silicified wood, which appears mostly within the same stratigraphic layer. The fossil wood within the lake sediments indicates significant vegetation during the Squaw Creek Member time, although all recorded are <0.4m in diameter. This suggests relative immaturity in the woody vegeetation. The pillow and partially invasive lava flow contact indicates that the sediment was still water-saturated, or a standing water body still existed in some parts, when the Roza flow was emplaced.

Figure 13: Diatomite interbed of the Silica Road locality (Squaw Creek Member), invaded by basalt of the Roza Member. Spiracle on the left side indicates blow-out of water steam.

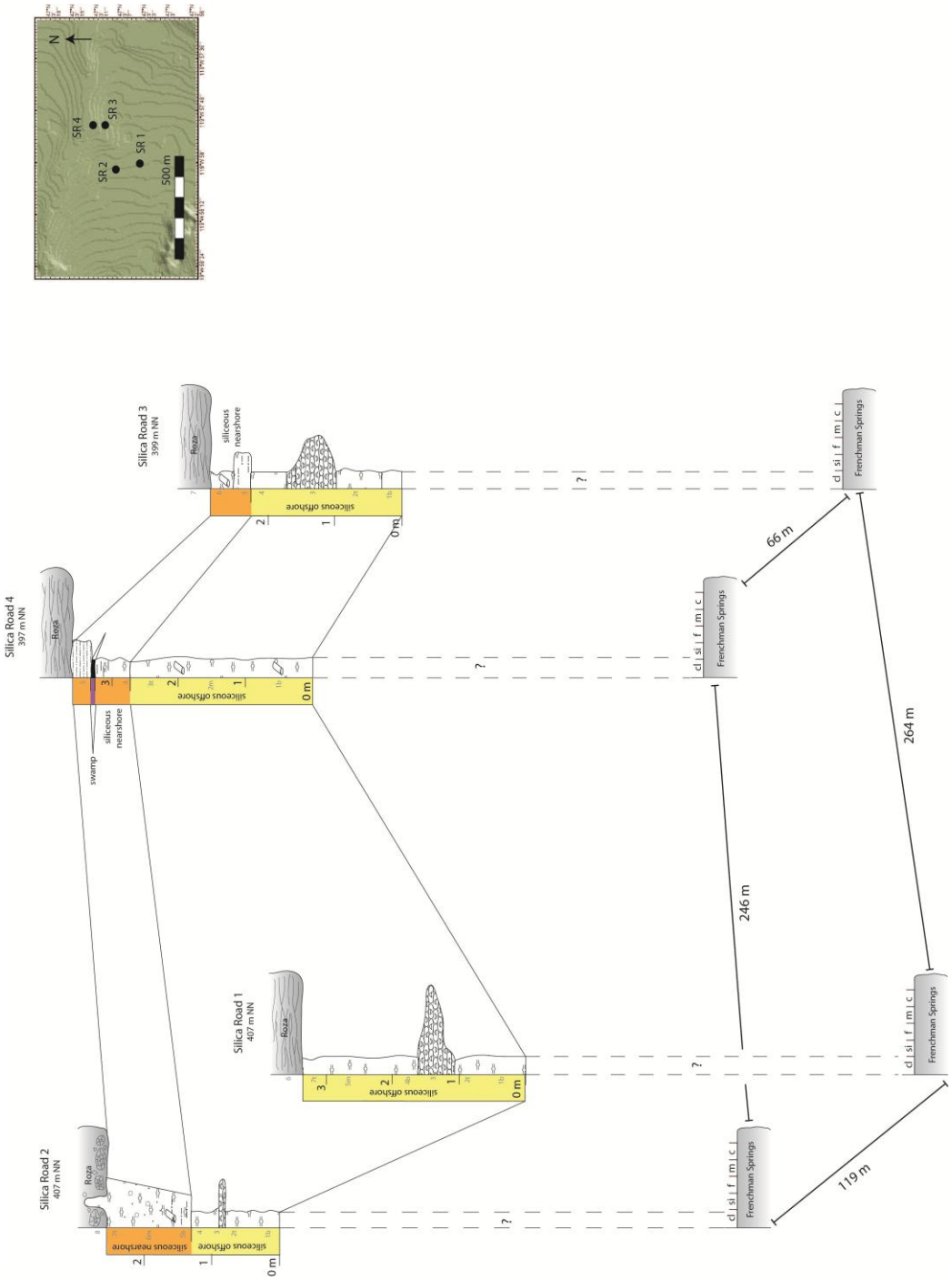

Figure 14: Correlation of 4 sedimentary logs of the Silica Road locality (Squaw Creek Member). Diatomite beds indicate sedimentation in siliceous lacustrine facies.

Stan Coffin Lake (SCL) Locality

The Stan Coffin Lake interbed has a logged thickness of 1.47 m and consists of interbedded coal, peat, yellow grey-coloured siltstone, diatomite to diatomaceous mud and chert lenses. The lowermost sedimentary unit (*c*. 8.0 cm) is a coarse-grained sandstone, which is intercalated with thin layers of diatomaceous mud that contains fossil plant debris. The sandstone is covered by a unit of interbedded coal (2.0 – 6.0 cm), diatomite (4.0 – 10.0 cm) and diatomaceous siltstone (3.0 – 10.0 cm). The diatomite beds may contain fossil wood debris. The middle part of the section is dominated by a *c*. 80.0 cm thick chert bed, which becomes less indurated and includes increasingly thin diatomite lenses within the upper 20.0 cm. The chert unit underlies a *c*. 24.0 cm thick bed of diatomite, which is overlain by a pillow-palagonite complex of the Roza Member (or Priest Rapids Member). The base of the interbed is not exposed (figure 15 A).

Interpretation

This section is interpreted as sediments deposited within a siliceous lake setting. The diatomite beds within the middle and upper part suggest rather distal deposition (offshore), whereas the siltstone and sandstone beds are related to a more proximal facies (nearshore). The coal layers indicate interbedded swamp facies, which might be related to alternating lake levels. The pillow-palagonite complex on top of the interbed indicates water-saturated conditions during the emplacement of the Roza Member (or Priest Rapids Member).

Trinidad (T) Locality

This interbed comprises 4 sections, which constitute a thickness between 0.47 and 1.74 m (figure 15 B and 16). The interbed is composed of basal light grey diatomaceous mudstone and siltstone, overlain by interbedded layers of brown, grey, red and yellow mudstone (multicoloured mudstone). The diatomaceous mudstone and siltstone beds show thicknesses between 8.0 and 40.0 cm, and are generally characterised by massive textures. Both contain fossil plant debris. Individual beds of the multi-coloured mudstones range in thickness between 0.1 cm and a few centimetres. Organic-rich layers are indicated by brown colours. Sections 2 and 3 are characterised by yellow and brown-coloured rhythmites within the upper part. Additionally, the interbed shows a high degree of induration in the top parts presumably due to heating by the upper lava flows. The interbed overlies vesicular and rubbly basalt of the Frenchman Springs Member and underlies brecciated to colonnaded basalt of the Roza Member. The contact with the Roza Member is further characterised by spiracles and invasive structures.

Interpretation

This interbed is the result of deposition within a shallow lake or wetland. Rhythmites and diatomaceous mudstone indicate sedimentation within a more quiet distal setting, whereas silt-rich layers suggest rather nearshore settings. The content of siliciclastic material suggests the (seasonal) connection to a fluvial system. The invasive character of the Roza Member and the spiracles

indicate soft sediment-lava interaction under water-saturated conditions.

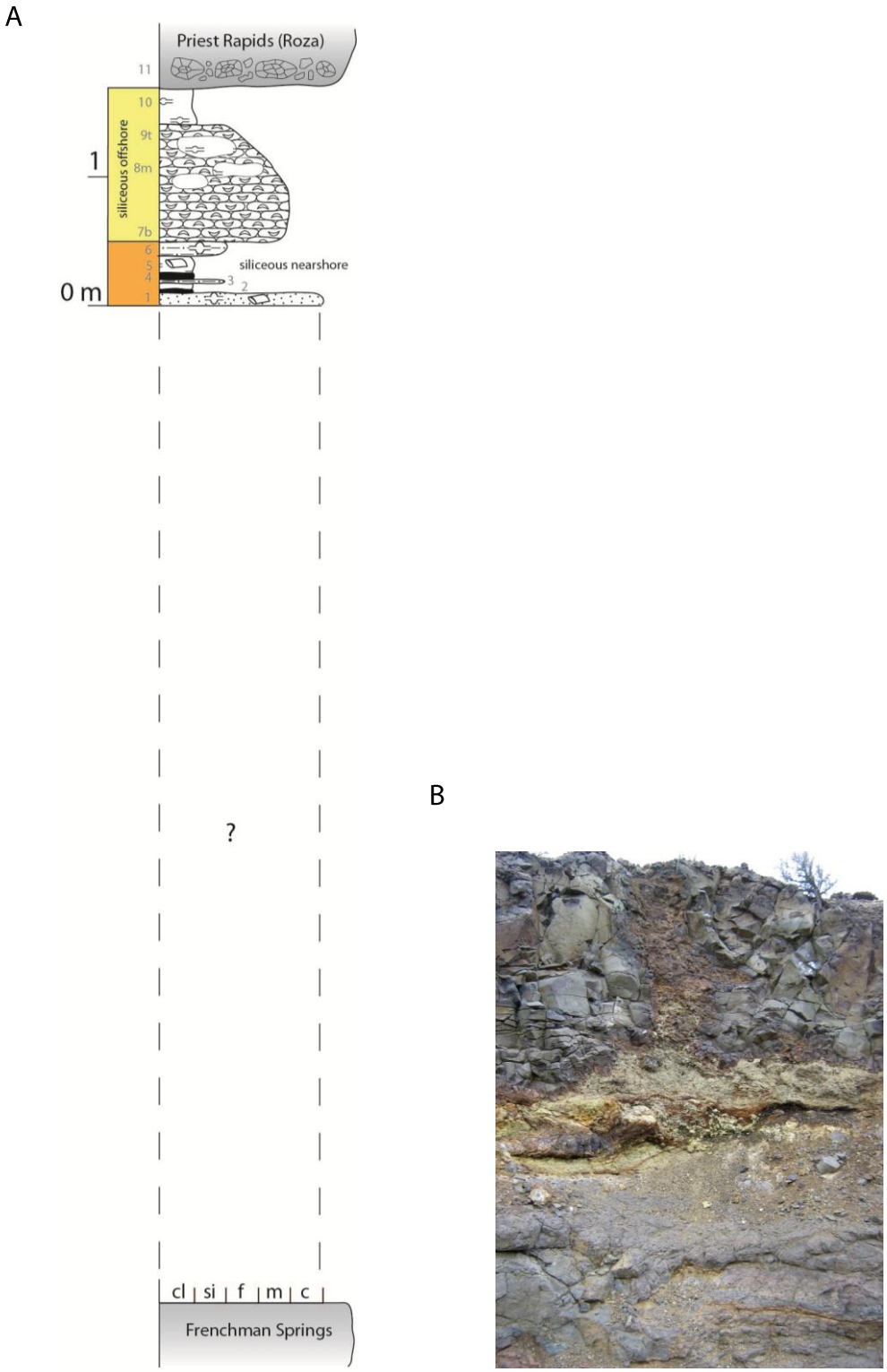

Figure 15: A) Sedimentary log of the Stan Coffin Lake interbed (Squaw Creek-Quincy Member) indicating deposition within a siliceous lake setting, with input of siliciclastic material. B) Thin mixed siliciclastic -diatomaceous interbed of Trinidad (Squaw Creek Member) with spiracle in the centre.

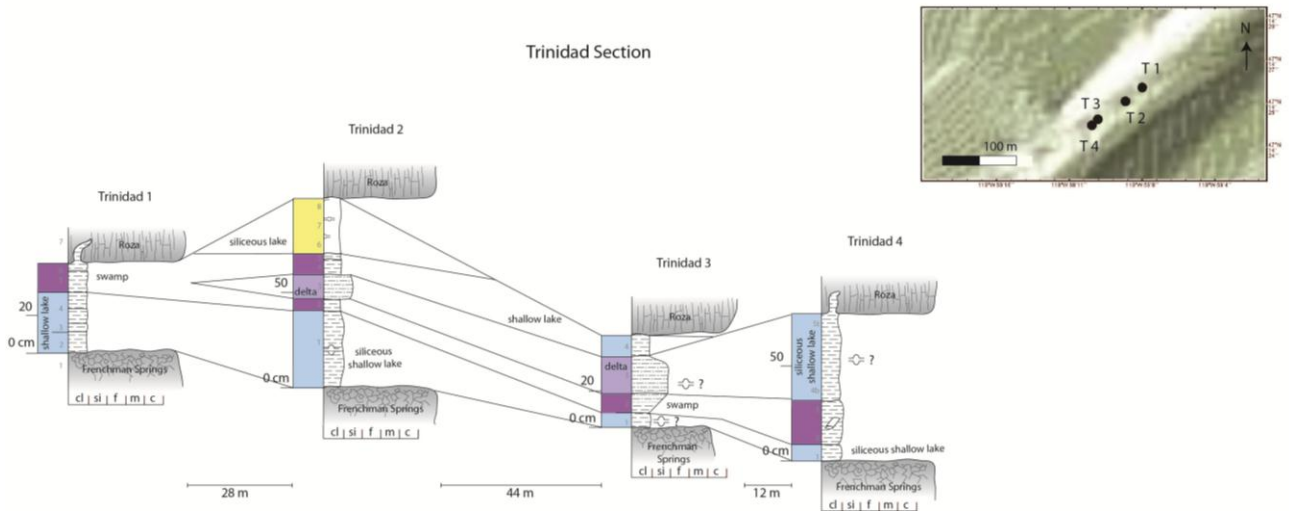

Figure 16: Correlation of sedimentary sections of the interbed (Squaw Creek Member). Lithology indicates deposition of siliciclastic and diatomaceous mud within a shallow lacustrine setting.

4.4. Rattlesnake Ridge Member

Mabton (M) Locality

The Mabton interbed includes one section with a thickness of 15.14 m. This section is defined by a basal thick unit (more than 8.0 m in total) of massive to planar laminated brownish siltstone and mudstone. This unit is in the middle part interbedded by up to 50.0 cm thick beds of fine- to medium-grained sandstone. These beds are characterised by wavey planar and trough cross-lamination with individual, and feature small-scaled load structures, flame structures and slumping.

The unit of mud- and siltstones is overlain by beds of tabular cross-bedded gravelly coarse-grained sandstone, with individual sets, which range in thickness from *c*. 10.0 to 80.0 cm. Foreset bedding is between 1.3 and 2.8 cm thick. This unit underlies beds of planar-bedded and cross-laminated fine-grained sandstone. Individual beds are generally a few decimetres in thickness. The upper part of the interbed is dominated by a *c*. 2.0 m thick unit of massive or planar bedded siltstone. Individual beds are up to 4.5 cm in thickness and contain debris of fossil wood (figure 18). The interbed lies on top of a reddish, blocky (weathered) basalt flow of the Pomona Member, and underlies a brecciated flow bottom of the Elephant Mountain Basalt.

Interpretation

This interbed is the result of fluvial deposition. The siltstone facies suggests accumulation during a stage of low energy; whereas the sandstone-gravel cross-stratification indicates an increase of input and flow energy. These sediments might be deposited on large migrating bars with small ripples on top. The massive sandstone beds suggest rapid deposition from suspension during floods or bank collapses within the channel.

Mabton-Bickleton Road (MB) Locality

Mabton-Bickleton Road comprises a *c*. 4.14 m thick logged sedimentary section. The section is

characterised by a *c*. 2.1 m thick basal unit of grey to dark grey interbedded mudstone and siltstone, which constitutes predominantly a massive texture or planar lamination at the bottom and wavey to cross-lamination at the top of the unit (figure 17 and 18). Individual beds of mudstone are a few millimetres and of siltstone a few centimetres thick. Sets of cross-lamination (within siltstone) are commonly 0.3 – 0.8 cm thick. Intercalated with this unit are lenticular beds of silty fine-grained sandstones with averaged bed thicknesses of 2.5 – 3.0 cm to up to 20.0 cm. The upper part of the unit is further characterised by the presence of rootlets and fossil wood. The upper part of the section is dominated by a *c*. 60.0 thick massive dark grey mudstone bed, which contains fossil wood and rootlets and which grades into more siltstone-dominated layer at the top. This layer shows a zone of shrinkage structures, which is *c*. 30.0 cm high with individual joints of up to 4.0 cm in width and up to 10 cm in length.. This layer is covered by a light grey bed of tuff of varying thickness (averaged thickness = 16.0 cm). The interbed is covered by massive, vesicular basalt of the Elephant Mountain Member. The lower lava flow is not exposed.

Interpretation

The intercalation of plant debris-rich mudstone, wavey to cross-laminated siltstone and fine-grained sandstone indicate a fluvial channel and proximal overbank environment.. The overbank setting includes an horizon of vertisol formation towards the top of the interbed.. The vertisol is covered by felsic tuff which suggests post-pedogenic accumulation by volcanic fall-out processes.

Figure 17: Siliciclastic fluvial overbank deposits at the Mabton-Bickleton Road locality (Rattlesnake Ridge Member).

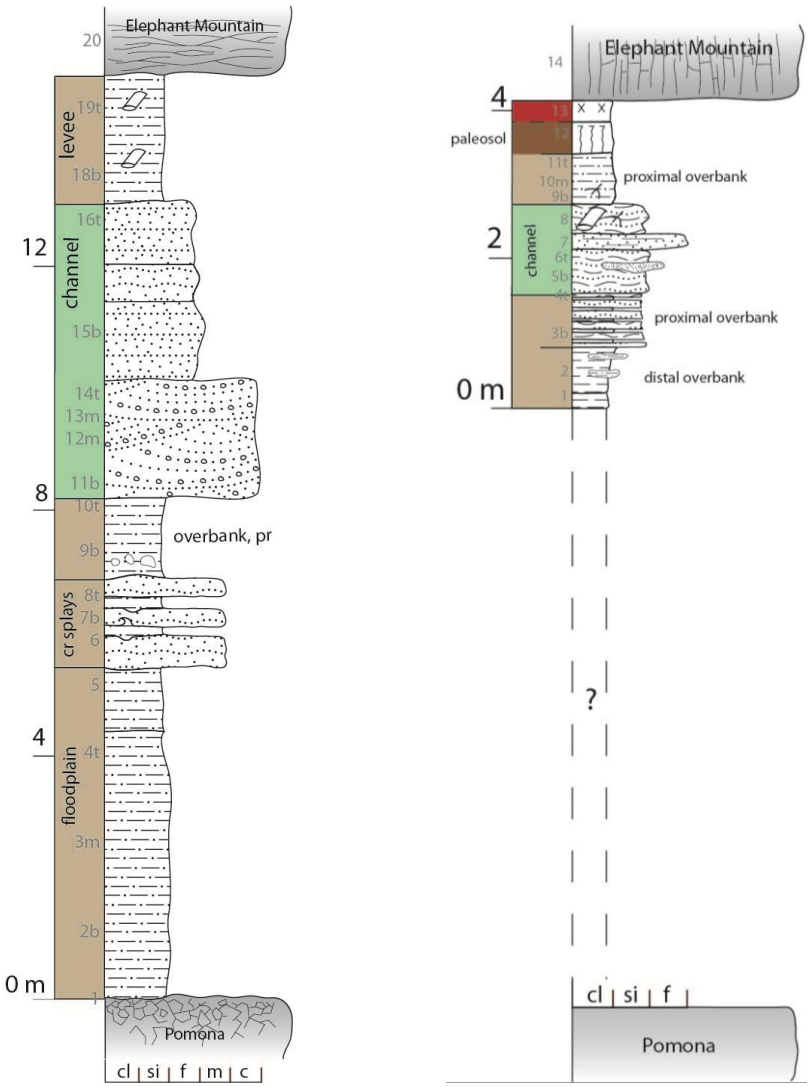

Figure 18: Sedimentary logs of the Mabton and Mabton-Bickleton Road location (Rattlesnake Ridge Member). Mabton represents fluvial channel and overbank deposition, while Mabton-Bickleton Road suggests clastic lake facies, which is probably associated with a fluvial environment.

Table 3: Summary of characteristics of sedimentary interbeds.

Location	GPS Coordinates	Lithofacies assemblage	Interpretation
Grande Ronde, R2 - N2 contact			
Wagon Road (WR)	N 46 52.931 W -120 25.463	Siliciclastic mudstone, cross-laminated, planar bedded sandstone, cross-stratified conglomerate	Fluvial overbank facies, cut by small fluvial channels and crevasse splays
Vantage Member			
Central Ferry (CF)	N 46 31. 529 W -117 48.277	Weathered basalt flow top	Ferralsol
Dodge (D)	N 46 39.769 W -118 13.658	Horizontally and massively bedded conglomerate	Fluvial channel fill
Estes (E)	N 46 39.959 W -118 13.454	Weathered basalt flow top	Ferralsol
Palouse Falls (PF)	N 46 39.031 W -118 31.003	Siliciclastic and diatomaceous mudstone, horizontally bedded sandstone	Wetland - shallow lake
Vantage (V)	N 46 57.086 W -119 59.520	Siliciclastic mudstone, cross-laminated, cross-bedded (pebbly) sandstone, planar bedded sandstone, massive sandstone	Fluvial channel fill and overbank deposition
Windust (W)	N 46 39.967 W -118 13.466	Weathered basalt flow top transitional to mudstone	Ferralsol
Squaw Creek-Quincy Member			
Caliche Lakes (CL)	N 47 01.277 W -119 56.575	Scoria and diatomite	Scoria, grading into siliceous lake deposits
Sulphur (S)	N 46 39.031 W -118 31.003	Siliciclastic mudstone	Wetland - shallow lake
Silica Road (SR)	N 47 03.079 W -119 58.004	Diatomite and diatomaceous mudstone	Siliceous lake
Stan Coffin Lake (SCL)	N 47 08.686 W -119 55.489	Siliciclastic and diatomaceous mudstone, diatomite	Siliceous lake
Trinidad (T)	N 47 14.553 W -119 58.490	Siliciclastic and diatomaceous mudstone, diatomite	Wetland - shallow lake
Rattlesnake Ridge Member			
Mabton (M)	N46 08.468 W120 01.534	Siliciclastic mudstone, cross-laminated, cross-bedded (pebbly) sandstone, horizontally bedded sandstone	Fluvial channel and overbank facies
Mabton Bickleton Road (MB)	N 46 06.771 W -120 03.271	Siliciclastic mudstone, cross-laminated sandstone, primary pyroclasts, vertisol	Fluvial channel and overbank facies

5. Palynological Evidence for Interbed Environments

5.1 Introduction to plant community ecology and interpretation

Many terrestrial sedimentary sequences demonstrate progression in plant community seral succession through the duration of their deposition, in general terms we refer to these stages of community ecology as early, mid and late succession.

Early successional communities are dominated by disturbance tolerant species such as 'mare's tails' (*Equisetum*) and, if the environment is humid enough, ferns and mosses. Following on from these, early mid successional communities are dominated by spores of ferns, but include the bryophyte spores, polypodiaceous fern spores and juglandaceous (Walnut/Hickory) pollen. In more recent volcanic terrains, primary succession has involved grasses and weedy angiosperms as key early colonists (Whitaker et al., 1989; Thornton, 2000). Evidence indicates that this niche was dominated by ferns in the early Paleogene.

Mid-successional vegetation is typified by the Fagaceae-Juglandaceae community, which may be the most diverse of those identified. Many of the taxa within this group occur within other communities, but at lower abundances. Fagaceous pollen attributed to *Cupuliferoipollenties*, (*Castanopsis – Lithocarpus* types) which are one of the dominant taxa in this grouping, occur in a wide variety of assemblages but decline in significance in late successional vegetation.

Late successional vegetation is dominated by a Taxodiaceae-Nyssaceae association (Dawn Cypress and Black Gum), which is of low diversity. A number of species important in early-mid and mid successional vegetation decline in importance and diversity in this community as they are eliminated by effective competition from Taxodiaceae-Nyssaceae mire species. Patchworks of disturbed areas within this late-successional community are inferred from the incursion of other species Other such taxa, including *Monocolpopollenites tranquilus*, *Retitricolpites retiformis* and *Tricolpites* cf. *hians*, have previously been noted as part of riparian vegetation groupings (Streigler, 1990; Jolley, 1997), characteristic of disturbed fluvial margin environments. Accompanying these species are a range of taxa of lesser significance that may represent disturbed vegetation or understory.

Distributed across the range of environments is the betulaceous grain *Alnipollenties verus*. This taxon has been suggested as an N-fixing early colonist in nutrient depleted soils (Chapin et al. 1994; Hobbie et al, 1998; Jolley et al., 2008). Its occurrence suggests that the soils were nutrient deficient across a range of profiles

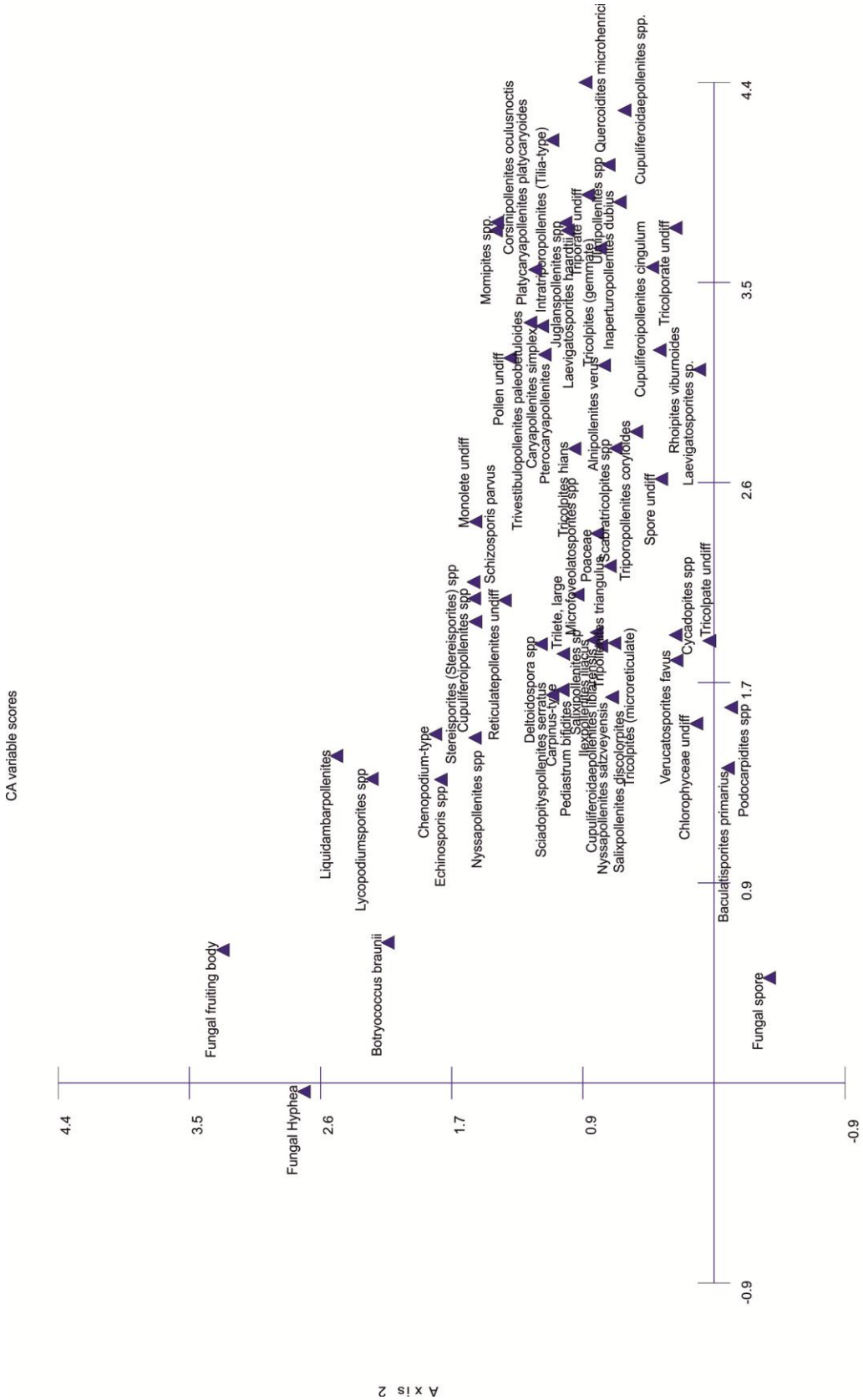
CA variable scores
Axis 1
Axis 2
4.4
3.5
2.6
1.7
0.9
-0.9
Fungal Hyphea
Fungal fruiting body
Botryococcus braunii
Liquidambarpollenites
Lycopodiumsporites spp
Chenopodium-type
Echinosporis spp
Stereisporites (Stereisporites) spp
Cupuliferoipollenites spp
Nyssapollenites spp
Reticulatepollenites undiff
Schizosporis parvus
Monolete undiff
Deltoidospora spp
Sciadopityspollenites serratus
Carpinus-type
Trilete, large
Pediastrum bifidites
Salixpollenites sp
Cupuliferoidaepollenites liblarensis
Nyssapollenites satzveyensis
Salixpollenites discolorpites
Tricolpites (microreticulate)
Microfoveolatosporites spp
Poaceae
Tricolpites hians
Scabratricolpites spp
Alnipollenites verus
Triporopollenites coryloides
Spore undiff
Verucatosporites favus
Chlorophyceae undiff
Cycadopites spp
Tricolpate undiff
Baculatisporites primarius
Podocarpidites spp
Fungal spore
Trivestibulopollenites paleobetuloides
Caryapollenites simplex
Pterocaryapollenites
Pollen undiff
Momipites spp.
Corsinipollenites oculusnoctis
Platycaryapollenites platycaryoides
Intratriporopollenites (Tilia-type)
Juglanspollenites spp
Laevigatosporites hardtii
Triporate undiff
Tricolpites (gemmate)
Alnipollenites spp
Inaperturopollenites dubius
Quercoidites microhenrici
Cupuliferoidaepollenites spp.
Cupuliferoipollenites cingulum
Tricolporate undiff
Rhoipites viburnoides
Laevigatosporites sp.

Figure 19. Correspondence analysis plot of values from the first two axes. Variation within the axis 1 is related to successional state, early succession communities are on the left of the diagram, mid/late succession communities on the right.

5.2 Ecological Analysis of Pollen and Spore Data

The principle objective of the palynofloral analysis in this study was to provide supporting evidence for interpretations of drainage system longevity and complexity. Analysis of the pollen and spore parent plant ecology was undertaken using a data set formed from the amalgamation of all field locations. This data set was then subjected to Correspondence Analysis (CA), which simplifies the most important variables of the data into two principle axes. The results can then be cross plotted (Figure 19), and groups of taxa with similar distribution identified. Cross plots of the first two axes of a CA analysis of pollen data similar to that from the CRBP normally generates plots which have one axis reflecting succession, and another moisture availability (see Jolley et al., 2012). However, in the case of the analysis in figure 19, this is not the case. Axis 1 can be seen to represent successional status by reference to the botanical affinity of the taxa recorded (figure 20).

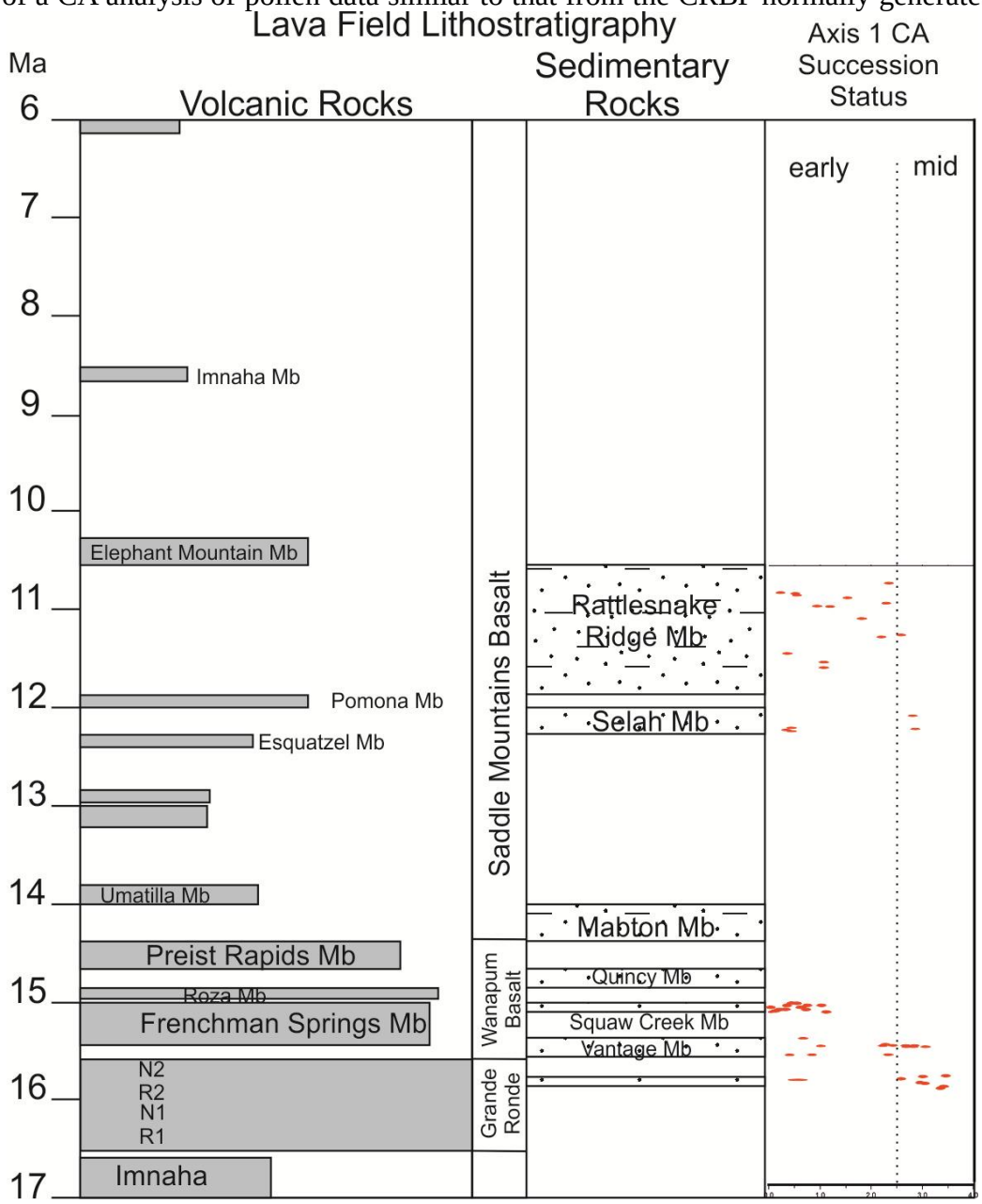

Figure 20. Stratigraphical plot showing the Axis 1 CA data (individual samples) plotted against the interbed using an approximate time duration for the flowfields. Note that the Axis 1 CA data suggests that the only true mid successional vegetation is recorded in the Grande Ronde R2/N2 boundary and Vantage interbeds.

Early successional palynofloras are present on the left of the diagram, while later succession floras occur on the right. Axis 2 does not appear to show any clear relationship to any one environmental vector,

Interpretation of the ecological analysis of the Columbia River data identifies the N2/R2 intra Grande Ronde interbed as being formed over an extended time period, possibly in excess of 8ky (figure 20). A similar, but probably longer interbed depositional hiatus is evident at the Vantage interbeds. The museum collection of fossil silicified wood held at Vantage Museum, Washington State contains a wide variety of conifer and broadleaved tree trunks recovered from the Vantage interbeds. The pinaceous coniferous wood probably originated as extra basinal material from upland areas (the current Cascades range) to the west. However, there are numerous specimens of *Taxodium* and *Nyssa* related wood types that indicate the occurrence of either a true swamp or transitional swamp vegetation for the Vantage interbed in the Vantage - Sentinel Gap area.

6. Evolutionary stages of the Miocene Drainage system

The members of the Ellensburg Formation are ascribed to 5 different evolutionary stages, spanning the period from the Early Miocene to the end of the Middle Miocene (*c*. 5 My). Interbeds at the R_2-N_2 contact of the upper Grande Ronde Basalt (*c*. 16 Ma) are ascribed to Stage 1, and interbeds of the Vantage Member to Stage 2. Due to similar depositional settings, the Squaw Creek and Quincy Members are related to Stage 3. Based on field observation and relations Stage 4 is related to the deposition of the and Selah Member. The youngest exposed member in the study area is the Rattlesnake Ridge Member (*c*. 10.5 Ma), which indicates the final stage of the drainage system for this time period.

6.1. Stage 1:Intra Grande Ronde time

Stage 1 is assigned to those sediments deposited at the R_2-N_2 contact of the upper Grande Ronde Basalt during the Early Miocene. The Grande Ronde Basalts represent the most voluminous eruption phase of the CRBP with the emplacement of approximately 150,000 km^3 of lava within *c*. 420,000 years. Eruptions probably lasted between decades to centuries and periods of quiescence are estimated at 1000 to up to 10,000 years (Reidel *et al*. 1989a, Barry *et al*. 2010). The areal extent of both R_2 and N_2 members completely covers the study area. The anticlinal ridges of the Yakima Fold Belt (dotted lines on figure 21) initiated during, or at the end of the eruption of the Grande Ronde Basalts. This resulted in significant topography of the upper surface of the Grande Ronde flows within the Yakima fold belt area. This is clearly demonstrated by the onlap of successively younger Wanapum Basalts onto the folded Grande Ronde Basalt surface in the Vantage area

The drainage system comprises fluvial channel and flood plains with rivers having their source areas northwest of the lava field. Due to the high eruption rate the drainage system was forced back to the margin of the lava field. The southwest dipping of the Palouse (palaeo-) slope suggests that fluvial streams could not penetrate the central part of the lava field and were redirected to the southwest.

Grande Ronde interbeds are characterised by a general fine-grained lithofacies including mainly mudstones, siltstones, fine-grained sandstone and intercalated fine-grained breccias and conglomerates. The sedimentary composition suggests source areas, which are mainly located within the lava field and have not been supplied with significant amounts of material from external catchments. Although the Grande Ronde R_2/N_2 interbeds were deposited during the maximum eruption tempo of the CRBP, the palynofloras recovered from these sedimentary rocks indicate one of the longest duration hiatuses, which supported mid succession vegetation with a complex composition. The palynofloras are characterised by pollen comparable to that from modern chestnuts, oaks, limes, elderflower types, alders, hickories and swamp cypresses. Along with these commonly occurring taxa are spores from polypodiaceous ferns that are commonly recorded as

forest/swamp marginal, or primary colonist species. These assemblages are in accordance with the wet, warm temperate Early Miocene regional climate. Palynofloras of this character are recorded at several horizons within the sampled successions, suggesting repeated mid successional communities were established and destroyed on the floodplains. This repeated re-generation of the floodplain vegetation, in contrast to a continuous ecological trajectory from early - late successional status, indicates that the fluvial overbank area ecology was re-set at periods =>2ky (Chadwick et al., 1999). However, there is no floral evidence for contemporaneous volcanism in these Grande Ronde interbeds above the lowermost beds. Rather, the frequency of N-fixing alder types is suggestive of longer term nutrient deficiency, volcanically fixed N and P being absent (Jolley et al., 2008). Disturbance of the overbank floral ecology was therefore not due to volcanic action, but resulted from the dynamics of the drainage system itself.

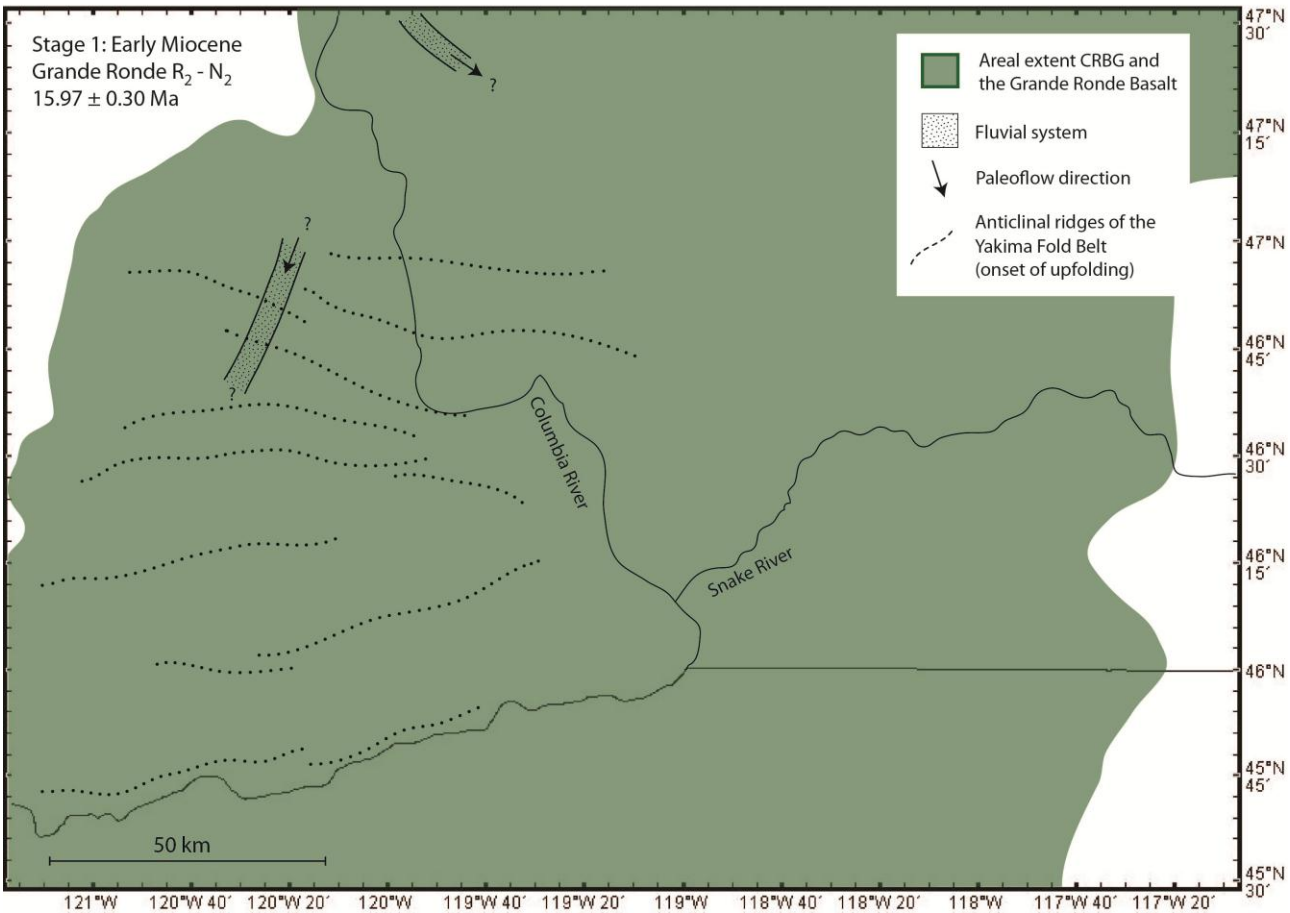

Figure 21: Evolutionary Stage 1 of the Miocene drainage system: Grande Ronde time, R_2-N_2 contact.

6.2. Stage 2: Vantage Member

Stage 2 of the drainage evolution is represented by the Vantage Member, which was deposited on top of the Grande Ronde Basalt (N_2 Member, 15.97 ± 0.30 Ma), during a period of quiescence that lasted presumably *c*. 110,000 years (Barry *et al*. 2010). The Vantage Member is overlain by the Wanapum Basalts (figure 22). At some localities (like Palouse Falls or Vantage) the overlying basalt can be further defined as the Palouse Falls or Ginkgo flows, respectively. This allows a more detailed illustration of the distribution of the overall Frenchman Springs flow field (marked by red line in figure 22).

The palynofloras recovered from the Vantage interbeds sampled are composed of a series of assemblages of mid successional character. Given that the estimated time durations (Jolley et al, 2008, Barry et al., 2010) are sufficient for the development of late successional floras, this in itself is evidence of repeated disturbance within the Vantage interbed drainage system. The character of these mid successional floras is also significantly different from that recorded from the older Grande Ronde interbed sediments. Abundant occurrences of green algae (dominantly taxa related to *Spirogyra* and *Botryococcus*) along with fungal spores and hyphae are characteristic of eutrophic lacustrine deposits in lava fields. The associated pollen and spore flora is dominated by hickory relatives (members of the Juglandaceae including *Carya* and *Platycarya* types), which are associated with alders and hornbeam types. Spores from floodplain ferns and fern allies also occur commonly. These pollen and spore associations are characteristic of a transitional swamp community associated with wetland lacustrine margins. The dominance of this lacustine and wet floodplain/lacustrine marginal flora is correlated to the pillow-palagonite nature of the overlying Ginkgo flow. To generate both the vegetation/algal community and the overlying volcanic facies would require wet substrates and standing water.

The drainage system of the Vantage time comprises fluvial streams with palaeoflow directions to the east and south east (figure 22). Apparently, they are restricted to the western part of the lava field away from the proximal eruptive zone. Rivers carried mostly sandy bedload, which are characterised by siliciclastic (quartz-rich), mixed volcaniclastic-siliciclastic or pumice-rich composition. The variation of composition indicates different source areas, which are mostly located outside the lava field. The mixed volcaniclastic-siliciclastic and pumice-rich interbeds suggest a provenance located in the Cascade Range, while the siliciclastic composition originates from intrusive and metamorphic rocks north of the lava field. Lakes existed on the lava field (e.g. at Vantage and the Palouse Falls localities), and are associated with high frequencies of lacustrine green algae. Further evidence of widespread land surface saturation is provided by the Ginkgo flow, a series of thick and widespread pillow-palagonite complexes. Investigations into volcanogenic nutrient fluxes suggest 10^{-3} to 10^{-4} years for the formation of the Palouse Falls interbed (Jolley *et al*. 2008), but the duration of re-establishment of the fluvial systems is still uncertain.

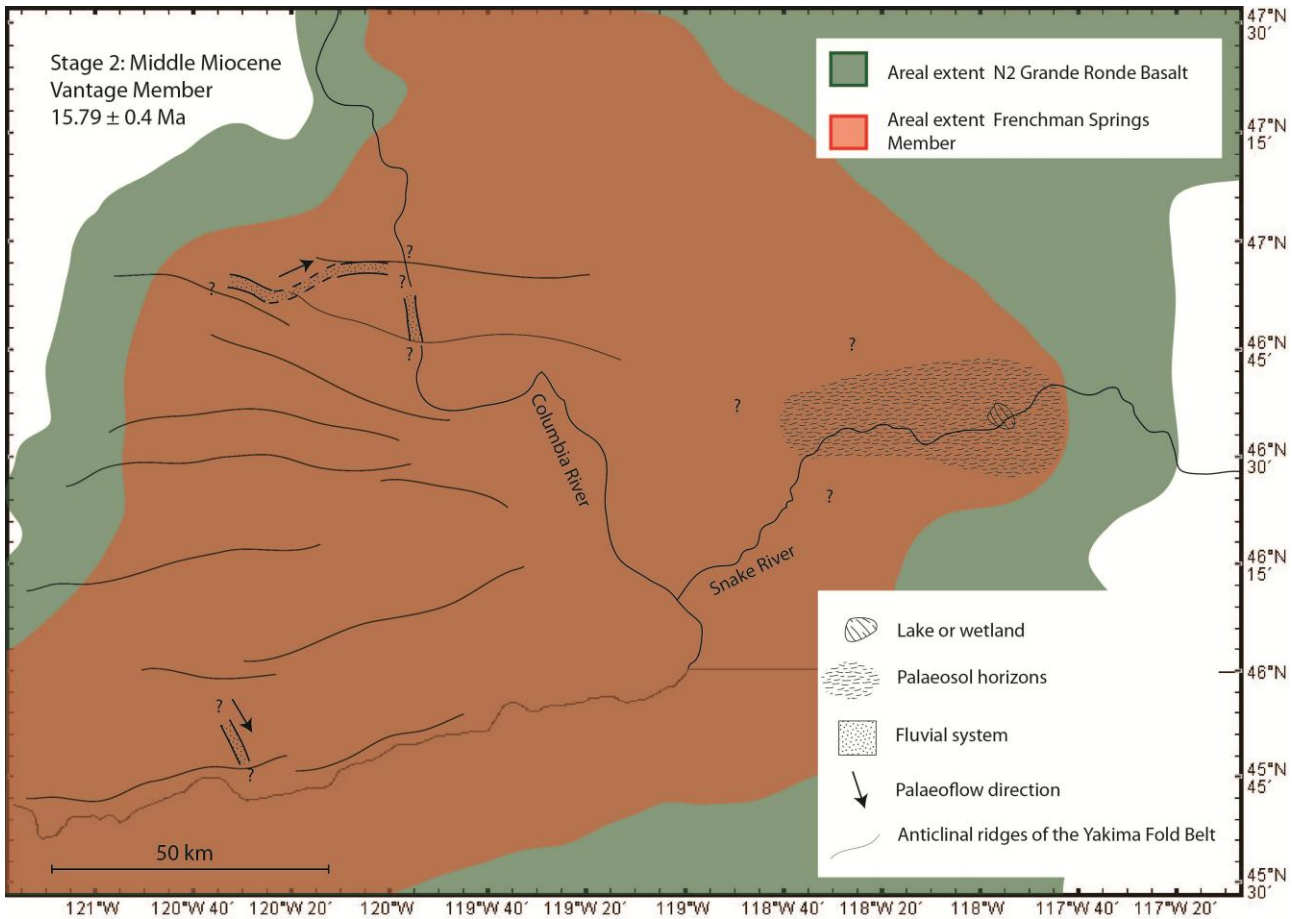

Figure 22: Evolutionary Stage 2 of the Miocene drainage system: Vantage Member time. The areal extent of the underlying Grande Ronde Basalt flow is showed by the green line, the extent of the overlying Frenchman Springs Member by the thick red line.

6.3. Stage 3: Squaw Creek-Quincy Member

The Squaw Creek and Quincy Members are assigned to Stage 3. The Squaw Creek Member was deposited between the Frenchman Springs Member and the Roza Member. Evidence from the palynofloras and interbed geochemistry demonstrate that the Squaw Creek Member was deposited syn-volcanically (Jolley et al., 2008). Localitites in the Vantage area received large volumes of volcanogenically fixed N and P from proximal fissure eruptions or flow skyights. The Quincy Member represents continuation of the Squaw Creek depositional system into the post-Roza Member period. Overlying the Roza Member, it is overlain itself by the Priest Rapids Member. The Quincy and Squaw Creek members are considered as one evolutionary stage because of related sedimentary settings.

The areal extent of the three main members, Frenchman Springs Member, Roza and the Priest Rapids Member (figure 23) defines the extent of contemporary accommodation space in the west of the lava field. The Stage 3 drainage system is dominated by a lacustrine facies distributed along the north western margin and central part of the Frenchman Springs, as well as along the north western and southern margin of the Roza and Priest Rapids Basalt (figure 23). The lacustrine settings include siliceous lakes (diatomites), clastic lakes (mixed siliciclastic-volcaniclastic composition), and very shallow clastic lakes or wetlands with a high amount of either (organic-rich) siliciclastic or biogenic sediments or tuffaceous material. Palynofloral assemblages recovered from these interbeds are similar to those reported by Jolley et al., (2008), being dominated by chlorophycean algae and fungal spores/hyphae. Along with common occurrences of fern and fern allies spores which are associated with wetland marginal environments, these data support an interpretation of deposition in emphemeral highly eutrophic lakes.

The stage 2 fluvial and lacustrine system was diverted out of the lava field area to the west by the Wanapum Basalts flow fields. Reduction of the lava eruption rate allowed the re-establishment lacustrine facies during Frenchman Springs Basalt eruption. This lowlying wetland facies was buried by the high volume flows of the Roza Member, the flows forming a widespread ponded facies. A combination of syn and inter volcanic sedimentation in this time interval is of interest. Although past the apogee of CRBP extrusion rates, the Frenchman Springs Member covers the largest areal extent after the Grande Ronde Basalt, having a volume of *c*. 6000 km^3 lava (Tolan *et al*., 1989) and reaches thicknesses up to >100 m. The Roza Member is of a smaller volume than the Frenchman Springs Member (*c*. 2000 km^3, Tolan *et al*., 1989) and thicknesses range between 15 and 50 m. Both are extensive topography-filling basalt plains flow fields in the west of the study area, lack of more significant sedimentary interbeds is most probably related to the absence of a significant break in eruption between the members.

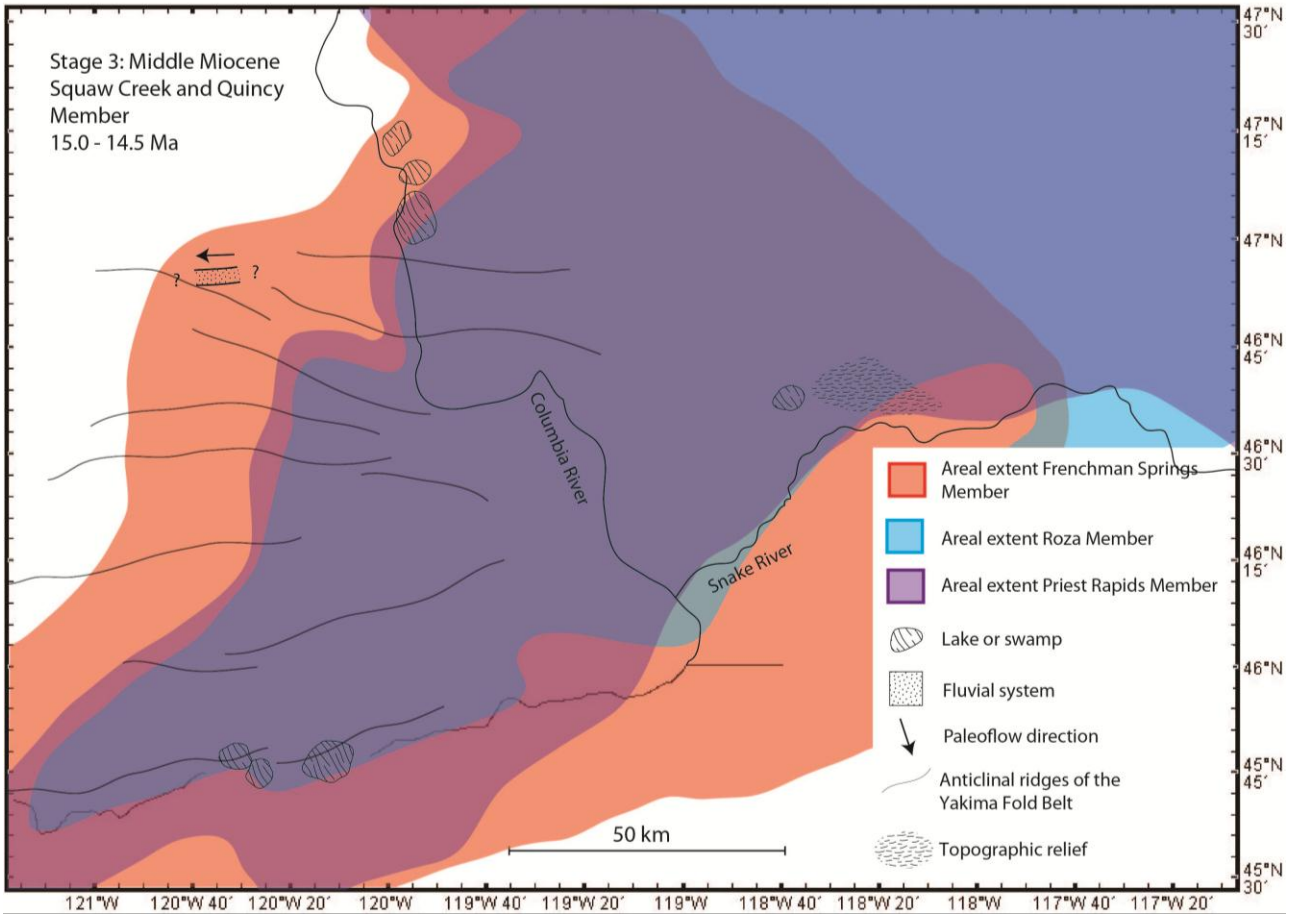

Figure 23: Evolutionary Stage 3 of the Miocene drainage system: Squaw Creek and Quincy Member time. The areal extent of the lowermost Frenchman Springs Member is shown by the red line, the middle Roza Member by the dark blue line, and the upper Priest Rapids Member by the bright blue line.

6.4. Stage 4: Selah Member

Distribution of the Wanapum Basalts was controlled by pre-existing accommodation space in bedrock valleys in the fissure proximal, eastern area. In the Pasco and Yakima basins, these flowfields filled the low-lying accommodation space created by continued subsidence of this area between the thermally supported eastern fissure zone and the Cascades Range. The Saddle Mountains Basalts follow a similar, but more restricted distribution pattern, again flowing through bedrock valley systems into the low lying western area of the lava field. This facies model (figure 24) shows the areal extent of the Priest Rapids Member, Pomona and the Elephant Mountain members. East of the Pasco Basin and at the south western margin of the main lava field the areal extent of the basalt flow follows narrow depositional pathways to the west. These are now exposed as basalt-filled valley systems, implying continued uplift of the fissure proximal, eastern zone of the lava field.

The basalt of the Umatilla Member has a total volume of *c*. 1200 km^3, the Wilbur Creek-Asotin Basalt *c*. 250 km^3, the Weissenfels Ridge and Esquatzel Basalt even less. However, the Pomona and Elephant Mountain Members resulted from volcanism with higher eruption rates and have a volume of *c*. 800 $km^3$and *c*. 700 km^3, respectively. The periods of quiescence became increasingly longer and lasted *c*. 200,000 years between the Umatilla and Wilbur Creek-Asotin Member *c*. 1.5 Ma between the Pomona and Elephant Mountain Member (Tolan *et al*. 2009). In these long periods between eruptions the Stage 4 drainage system was developed.

The Stage 4 drainage system consists of at least 2 west and southwest flowing fluvial streams (figure 24). Based on paleocurrent data both river systems entered the lava field from the north west and south east, flowing along the north western and the south eastern margin. They probably joined before they left the lava field through the river valley to the south west. Rivers carried sandy bedload material predominantly, which includes an increasingly proportion of basaltic gravel, as well as metamorphic basement and intermediate igneous rocks.

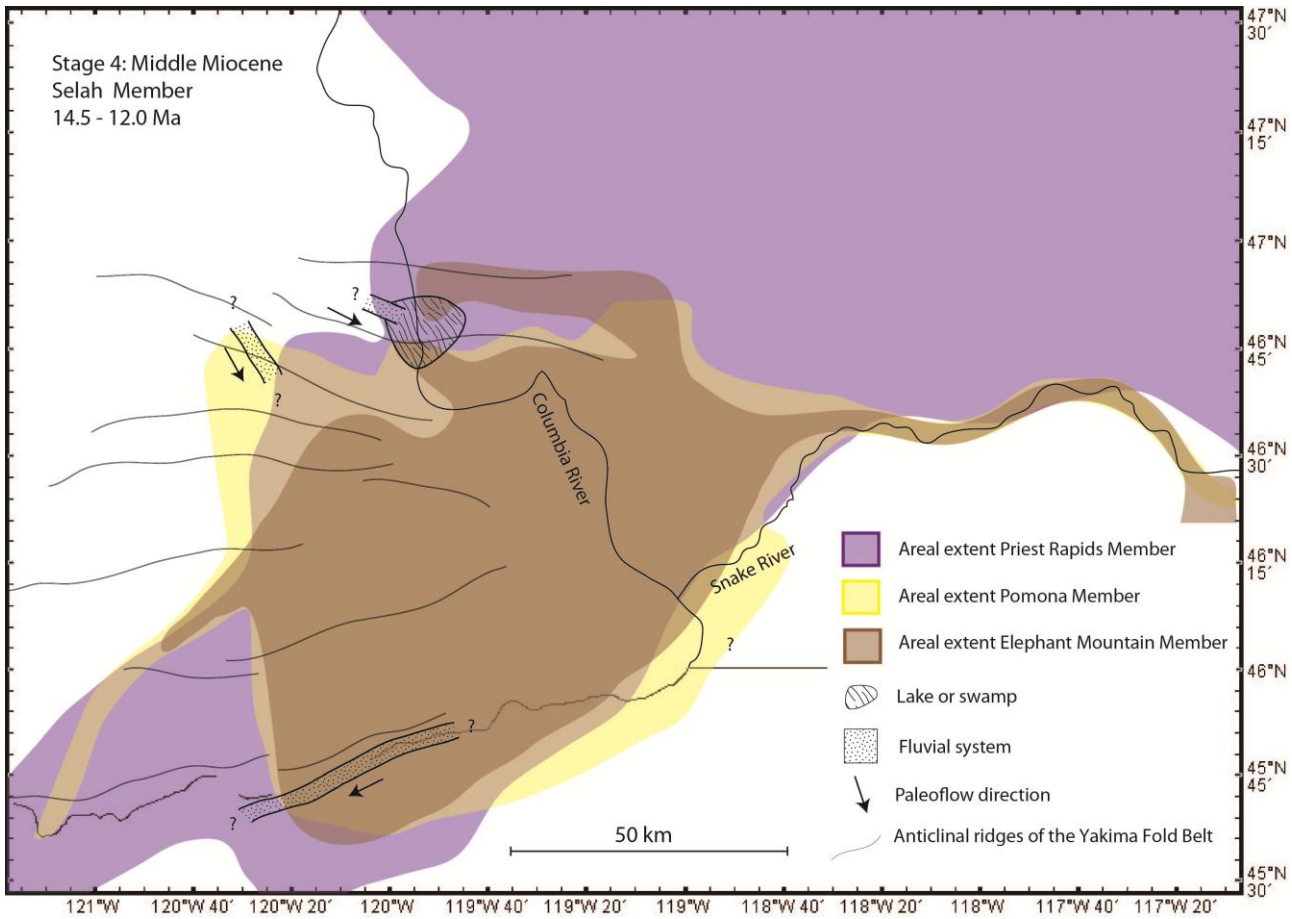

Figure 24: Evolutionary Stage 4 of the Miocene drainage system: -Selah Member time. The areal extent of the lower most Priest Rapids Member (purple), Pomona (yellow) and the uppermost Elephant Mountain Member (brown).

6.5. Stage: Rattlesnake Ridge Member

The Rattlesnake Ridge Member represents the youngest stage and was deposited during a quiescent period between the Pomona and Elephant Mountain Member (figure 25). During the Rattlesnake Ridge time well established drainage systems existed in the CRBP, with at least 3 different fluvial systems being identified. They entered the lava field from the northwest, northeast and east and left the lava field to the southwest (figure 25). The narrow path of the Pomona and Rattlesnake Member at the south western end suggests a narrow eroded river valley. It is assumed that the 3 fluvial systems merged before draining to the south east. The narrow ribbon-like exposure of the Pomona and Elephant Mountain basalts at the eastern margin of the lava field suggests the presence of eroded valleys. Some of these valley systems are exposed, eroded into the older Wanapum Basalts, connecting the fissure eruption zones in the east with the flood basalt plain in the west. The most southern drainage system is characterised by a wide variation of paleocurrents. However, the western dipping of the Palouse Slope suggests a western or south western main flow direction.
The varying paleocurrents of the Rattlesnake Ridge Member are probably related to a broad fluvial plain with one or several streams. This was apparently superimposed onto the flood basalt plain of the Pomona Member. Fluvial streams carried a variety of bedload during the Rattlesnake Ridge Member time, but are dominated by sand-sized bedload of mixed siliciclastic-volcaniclastic material. Additionally, interbeds exist, which are characterised by deposition of pumice-rich beds and polymictic conglomerates including gravel from a metamorphic and intermediate igneous source areas.

The dominance of arenaceous material in the Rattlesnake Ridge Member is reflected in the poor palynofloral record from several localities. Where palynofloras are recovered from ‘overbank’ facies, they are early successional, lacustrine assemblages. These show similarity to the associations recovered from the Squaw Creek – Quincy members interbeds and point to a rapid and repeated cycle of disturbance and regeneration associated with lake formation on a relatively flat basalt plain. While the dominance of arenaceous material in this interbed succession has undoubtedly affected the fossil record, the lack of any well developed mid successional plant communities in the sampled overbank facies points to repeated disturbance by fluvial channels in a dynamic system.

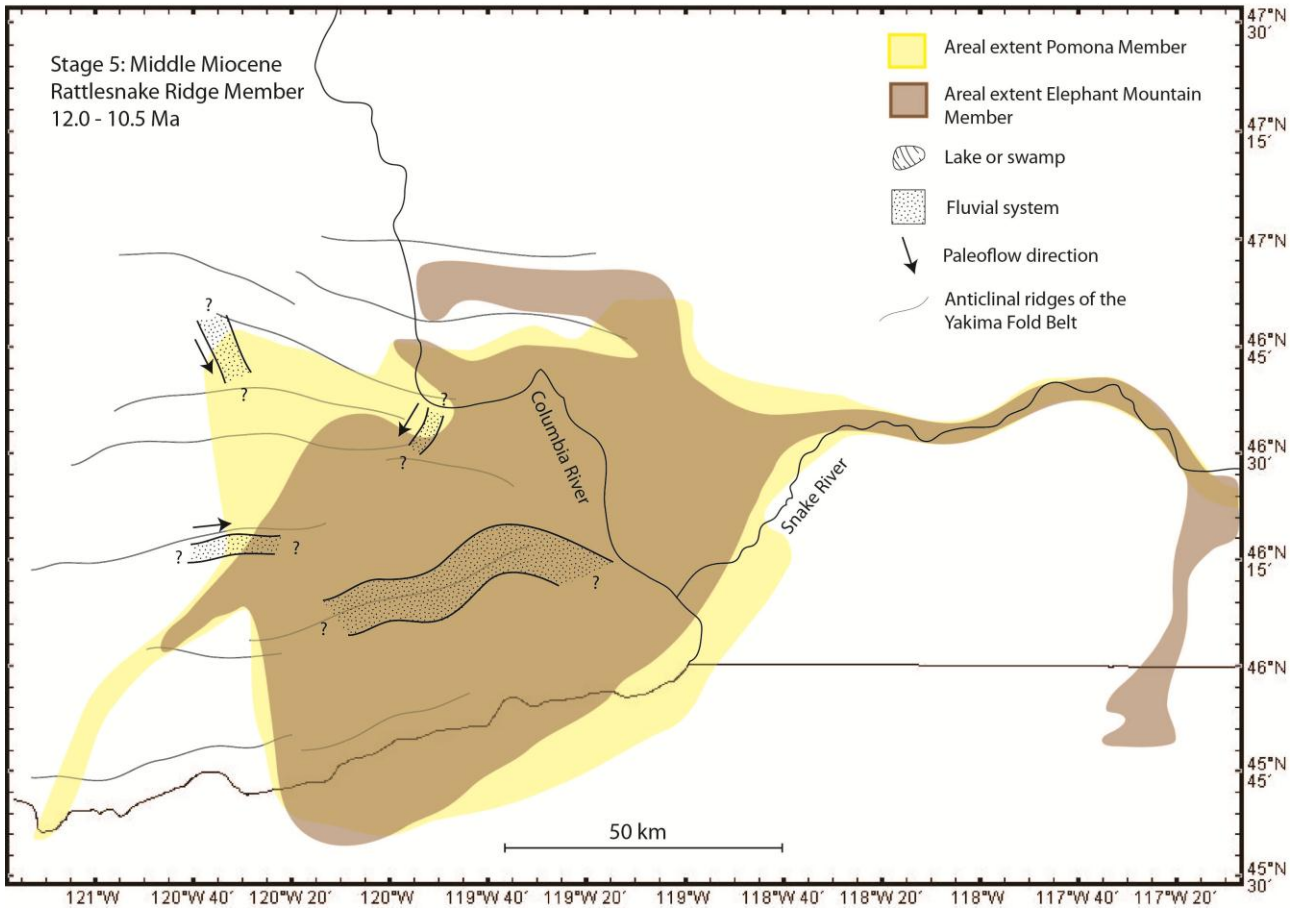

Figure 25: Evolutionary Stage 5 of the Miocene drainage system: Rattlesnake Ridge Member time.

7. Formation of lakes within the Columbia River Basalt Province

The formation of lakes and rivers within a continental Large Igneous Province (LIP) is controlled by various factors. Based on the data present four major types of lacustrine settings existed: 1) siliceous lakes, 2) clastic lakes and 3) mixed shallow lakes or wetlands. Siliceous lakes are characterised by the deposition of diatomaceous mud, which may be interbedded with thin layers (several centimetres in thickness) of siliciclastic and/or volcaniclastic organic-rich mud, silt and fine-grained sandstone. Chert nodules and lenses are common within layers with a high proportion of diatomite or volcaniclastic sediment. These interbeds commonly constitute thicknesses of at least 2.2 m. Field observations revealed lower brecciated flow contacts. The lack of significant fluvial input suggests isolation from a fluvial system. Presumably, such lakes were formed by lava-rise or lava-subsidence pits (lava-generated topography). Lava-rise pits are associated with irregular rates of inflations during emplacement and cause a micro relief on top of a lava flow . Lava-subsidence pits are collapse pits of partially solid crust and still viscous lava (cf. Ballard *et al*. 1979).

Clastic lake deposits include intercalated volcaniclastic mudstone, diatomaceous mudstone, siltstone, fine-grained sandstone, peat or coal and fine-grained breccia or conglomerate. Beds of fine-grained rhythmites (laminae) or ash (vitric tuff) may exist in some areas. The interbeds range in thickness between *c*. 1.25 m (exposed thickness) and 24.0 m. The lithofacies suggest a regular or seasonal connection to a fluvial network and field observation revealed basal and upper fluvial sediments in some places. The sedimentology of these interbeds suggests deposition within lakes, which were associated with a river system like oxbow lakes or wetlands, lakes and swamps on flood plains (cf. Collinson, 1996). Lacustrine sediments, which are interbedded with thick beds of fluvial deposits, may indicate periodic damming of pre-existing river channels by lava flows or heavy ash fall out deposits. Lava flows, which enter a river valley, cause ponding of a lake along the lobe front resulting in avulsion and re-establishment of a new fluvial flow path once the ponded water level has risen to a breach point.

Mixed shallow lakes or wetlands are characterised by beds of volcaniclastic, siliciclastic, tuffaceous and/or diatomaceous mudstones, , sandstones, coal or peat layers and very fine-grained breccias or conglomerates. Interbed thicknesses are commonly below 1.5 m. The lithologies of these lacustrine interbeds suggest shallow lakes or wetlands eventually associated with a fluvial system like oxbow lakes or lakes, swamps and wetlands on floodplains.

8. Formation of Fluvial Systems within the Columbia River Basalt Province

It is clear from the interbed log data that significant extrabasinally derived fluvial systems are present in the thicker (>3.5 m thick) of the studied interebeds. The provenance and palaeocurrent data indicate that much of the drainage was derived for the proto-Cascades area to the northwest, suggesting relatively large mature catchments and transport distances > 100 km. The stacked nature of foresets where developed indicate a relatively long-lived channel system, an interpretation supported by the maturity of the associated overbank flora.

It is interesting to note that channel systems are only associated with thicker interbeds suggesting both a time and accommodation control on their development. The channel systems needing a significant time period to encroach across the pre-existing lava field and the accommodation space to aggrade and onlap the lavas. Thinner interbeds without channel systems were clearly isolated from extrabasinal drainages and developed solely within the lava field itself.

In terms of reservoir quality. The fluvial channel deposits all contain a relatively minor proportion of basaltic material despite being located on pre-existing lava fields. This indicates only a limited input from drainages developed on the lava field. This is to be expected as the extrabasinal catchments are likely to be much larger than those present on the volcanic edifice and will therefore swamp any locally derived volcaniclastic input.

In terms of analog reservoir extent, the nature of the outcrops means that it was often difficult to get dimensional data for more than a few hundred metres laterally at most, and in many cases only a few tens of metres. What is clear though, is that in all the thicker interbeds (>3.5 m) significant clean, extrabasinally-derived fluvial sands are present. Net to gross was variable but rarely went below 30% which is commonly considered to be the cut-off for 3D connectivity in fluvial systems.

Direct comparison may be drawn between the intra Grande Ronde Basalt depositional system and the upper, fluvial dominated parts of Faroe-Shetland Basin interlava reservoirs (e.g. Rosebank). This comparison is based on the close similarities in the structure of the floodplain and surrounding flowfield ecology derived from the palynofloras.

In summary, in the thicker interbeds developed around the flanks of the volcanic edifice, clean, extrabasinally-derived fluvial channel deposits are present between lava flows with reasonable to

good connectivity. These are directly linked to significant hiatuses in eruption, and to subsidence within the western, peripheral part of the lava field. In the centre of the CRBP, proximal to the fissures of the Cheif Joseph Dyke Swarm, the constructional volcanic edifice was internally drained and lake systems were developed, extrabasinal fluvial systems do not occur and the area would have little or no reservoir potential.

9. Conclusions

The Miocene drainage system in the Columbia River Basalt Province is characterised by a network of meandering river channels, lakes and wetlands, associated with paleosol horizons. Based on sedimentological logging and paleo-current data, 5 distinct evolutionary stages of the drainage system are differentiated. Stage 1 and 2 during the Grande Ronde Basalt time and following deposition of the Vantage Member represent the re-establishment of a drainage system during a phase of high eruption rates. Fluvial streams were forced back to the margin of the lava field, and a few lakes were formed by lava-subsidence or lava-rise pits. Basalt flow tops in the central area of the lava field were subject to intense weathering and formed thin reddish soil horizons. Stage 3 (Squaw Creek and Quincy Member) was dominated by lacustrine facies and represent an early stage of waning volcanic activity. The drainage system dominates the margin of the lava field. Stages 4 and 5 include interbeds of the Saddle Mountains Basalt (Selah to Rattlesnake Ridge Member) and represent the ongoing re-establishment of a predominantly fluvial drainage system during the phase of waning volcanic activity.

Sedimentation and distribution of sedimentary bodies within the lava field was controlled by the distribution of lava flows. During Stage 1 and 2 the volcanic activity produced large volume flow fields, covering wide areas and filled river valleys. With the continuous decline of volcanic activity during the Wanapum and Saddle Mountains Basalt time, drainage systems occupied the same geographical space as the more limited flood basalt plains.

Uplift of the Yakima Fold Belt probably started during the eruption of the Grande Ronde time (Reidel 1984). The affect of these anticlinal ridges on the distribution of the drainage system is not fully understood. However, younger basalt flows and interbedded sediments thin out on the ridges and thicken in the valleys. This suggests syn-volcanic and syn-depositional uplifting during the Wanapum and Saddle Mountains Basalt time, although growth rate slowed down by the end of the Miocene (Reidel 1984). These folds created accommodation space for fluvial systems, lakes and subsequent lava flows, and most probably controlled the local drainage directions.

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