

## New stratigraphic markers in the late Pleistocene Palouse loess: novel fossil gastropods, absolute age constraints and non-aeolian facies

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### ABSTRACT

Four stratigraphic sections in the southern part of the Columbia Basin preserve a sequence of aeolian and non-aeolian sediments ranging in age from 9.43 to >47.0 <sup>14</sup>C ka based on accelerator mass spectrometry radiocarbon dating of fossil molluscs, geochemistry of Cascade Mountain-sourced tephra and association with formally recognized pedostratigraphic units (the Washtucna and Old Maid Coulee soils). Study sections are interpreted as representing concurrent deposition of loess and distal Missoula Flood rhythmites in valleys tributary to main drainages backflooded during the Missoula Floods, and formation of carbonate and iron-rich soils. Sediments belong to the formally recognized L-1 and L-2 loess units established for the Palouse loess, which were deposited in the Columbia Basin subsequent to events of glacial outburst flooding. Sediments associated with the Mount Saint Helens set S and set C tephras in the study sections preserve a fauna of five species of gastropod mollusc which have not been reported previously from sediments of late Pleistocene age in the Palouse region. The fossils comprise two distinct faunules stratigraphically separated by the Mount Saint Helens So tephra. Accelerator mass spectrometry radiocarbon dating of the fossils collected above the tephra in two of the sections yielded ages of 12.48 ± 0.06 and 9.43 ± 0.05 <sup>14</sup>C kyr. These ages suggest that independent determinations of the 13.35 <sup>14</sup>C kyr age of the So tephra in other areas where Missoula Flood sediments are preserved are probably accurate, and help to refine the age of the latest events in the most recent sequence of catastrophic glacial outburst flooding.

**Keywords** Loess, Missoula Floods, mollusc, Mount Saint Helens, Pleistocene, soils.

### INTRODUCTION

Regions sculpted by Quaternary glaciations, including North America, commonly have covers of thick, undifferentiated loess deposits left behind as signatures of these events. These massive loess deposits can be a few to over 100 m thick, making it difficult to discern both

the relative chronology and absolute age of the sequences. While typical stratigraphic indicators such as fossil vertebrates are abundant in the Pleistocene Palouse loess of Washington State, they are uncommon in other Quaternary units of the north-western USA, such as the Missoula Flood deposits (Rensberger *et al.*, 1984; Spencer, 1989). Field work conducted for the present

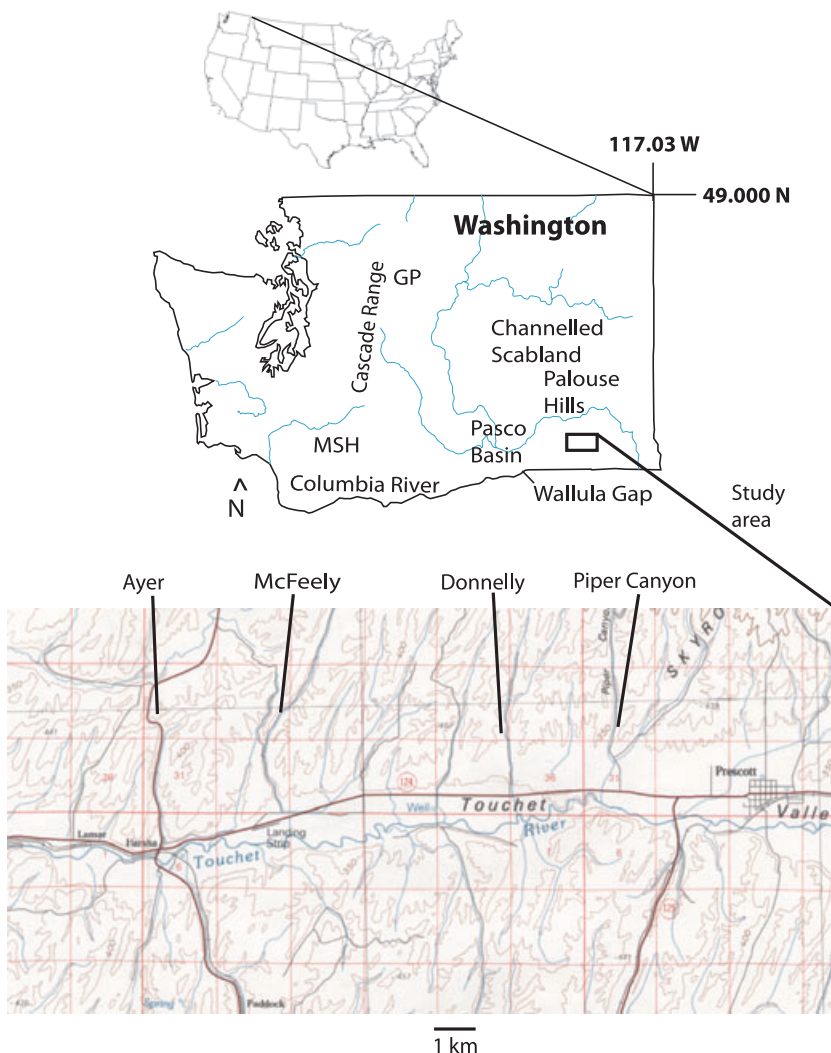
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report indicates that previously undocumented fossil terrestrial gastropods are common in certain facies of the Palouse loess, providing another tool with which to identify and correlate geographically discrete loess outcrops. This report provides age, stratigraphic and sedimentological data and interpretations for four study sections in southern exposures of the Palouse loess and documents the stratigraphic and sedimentological context for five species of gastropod mollusc. In addition, absolute age constraints are established for the gastropod-bearing intervals in the McFeely Road and Piper Canyon sections (Fig. 1) based on accelerator mass spectrometry (AMS) radiocarbon dating of shell material. Finally, the relationship between the study sections and the late Pleistocene slackwater deposits generated by the Missoula Floods (the Touchet Beds) are interpreted.

The sections studied are located approximately 25 km north of Walla Walla, Washington, and are exposed in shallow, ephemeral stream valleys tributary to the Touchet River, and on the drainage divide between the Touchet River and Eureka Flat to the north. Location of study sections and physiographic features mentioned in the text are shown in Fig. 1.

### REGIONAL GEOLOGICAL SETTING

The bedrock of the Palouse Hills of south-eastern Washington comprises a thick sequence of basalt flows assigned to the Miocene Columbia River Basalt Group (CRBG), which is overlain by, and interbedded with, several lithostratigraphic units. The Ellensburg Formation (Miocene), exposed in the western portion of the Columbia Plateau,



**Fig. 1.** Index map of Washington state and study area showing the locations of the study sections in central Walla Walla County and physiographic features mentioned in the text. MSH, Mount St Helens; GP, Glacier Peak.

comprises a sequence of tuffaceous fluvial and lacustrine sediments derived from the rising Cascade Mountains, which was distributed eastward across the developing Yakima fold belt (Smith, 1988). The Miocene to Pliocene Ringold Formation overlies the CRBG in the Pasco Basin (Fig. 1) and is interpreted as representing deposition by rivers draining the Rocky Mountains (Lindsey, 1990).

The CRBG, the Ellensburg Formation and the Ringold Formation are overlain by an extensive aeolian silt and sand deposit informally known as the Palouse loess. The age of the Palouse loess varies widely within the Pleistocene and Holocene. Cascade-sourced tephra and palaeomagnetism provide absolute and relative age markers in the unit; distinctive carbonate palaeosols (for example, the Washtucna and Old Maid Coulee soils of McDonald & Busacca, 1992; Busacca & McDonald, 1994) are useful physical markers. Interbedded with the Palouse loess are at least four, and perhaps as many as six, distinct sedimentary sequences representing periods of catastrophic glacial outburst flooding (McDonald & Busacca, 1988, 1992; Busacca & McDonald, 1994; Bjornstadt *et al.*, 2001; Spencer & Jaffee, 2002). The most recent flood sequence originated at glacial Lake Missoula in western Montana and is known as the Missoula Floods; earlier flood sequences are of unknown origin. Flood sequences are distinguishable from each other by bounding unconformities (Spencer & Jaffee, 2002); sedimentary textures and structures distinguish them from the associated loess.

The Palouse loess comprises a thick and monotonous sequence of fine-grained aeolian sediment derived from the Pasco Basin to the west of the Palouse region (McDonald & Busacca, 1992; Busacca & McDonald, 1994). Sites studied for this report show that, in central Walla Walla County, the loess is associated with sediment deposited by non-aeolian processes; stratification, graded bedding and variations in texture indicate aqueous deposition for these occurrences.

## STRATIGRAPHIC AND PALAEOLOGICAL FRAMEWORK FOR THE PALOUSE LOESS

Rensberger *et al.* (1984) established a biostratigraphic framework for the Palouse loess and provided ecological and taxonomic data, based

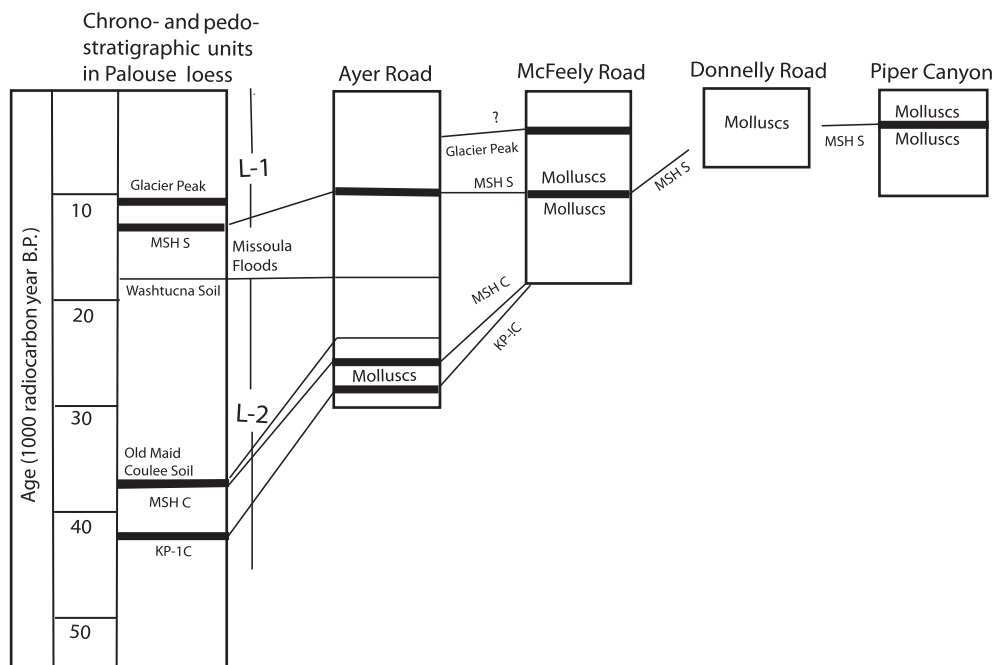
on the occurrence of small mammal fossils in a section spanning at least the last 40 kyr and perhaps as much as the last 100 kyr. Busacca *et al.* (1992) and McDonald & Busacca (1992) developed a correlation scheme for outcrops of younger loess in the southern Channelled Scabland (Fig. 1) based on stratigraphic and sedimentological features, including stratigraphic sequence, soil development and tephra chronology. Busacca & McDonald (1994) recognized and named two loess units: the L-1 [stratigraphically above the Mount St Helens (MSH) set S tephra] and L-2 (stratigraphically below the MSH set S, and including the MSH set C tephra near its base). The position of the loess units was defined further with respect to distinctive carbonate palaeosols including the Washtucna soil, which occurs beneath the MSH set S tephra, the Old Maid Coulee soil, which contains the MSH set C tephra, and the Devil's Canyon soil, which forms the lower boundary of the L-2 loess unit.

## STRATIGRAPHIC AND SEDIMENTOLOGICAL CONTEXT OF STUDY SECTIONS

### Ayer Road section

The Ayer Road section (Figs 1 and 2) comprises about 15 m of massive silt and fine sand with multiple horizons of carbonate soil and three recognizable tephra, exposed at an elevation of about 385 m. Based on the identity of soils and associated tephra, the Ayer Road section includes the L-1 and L-2 loess of Busacca & McDonald (1994), as well as the upper portion of an older, unnamed silt unit.

One of the soils is identified as the Washtucna soil (of McDonald & Busacca, 1992) based on distinctive morphological features, such as stage of soil development and close association of two stacked soils, and its stratigraphic position above a tephra identified as an MSH set C and below a tephra identified as an MSH set S (see Table 1 for tephra glass compositions). A second soil is identified as the Old Maid Coulee soil by its association with the MSH set C tephra. A third tephra consisting of a dark grey, fine-grained, indistinct layer occurs beneath the MSH set C. The distinctive physical appearance and stratigraphic position of this tephra beneath the set C tephra and the Old Maid Coulee soil make it a useful marker. This lower tephra unit (the KP-1C



**Fig. 2.** Correlation of study sections in Walla Walla County with recognized pedostratigraphic and tephra units in the central Columbia Plateau (Busacca & McDonald, 1994). MSH, Mount St Helens. No scale intended.

**Table 1.** Oxide compositions of glass in tephras from study sections (SD in parentheses).

Oxide	McFeely #1	McFeely #2	Piper Canyon	Ayer Road #1	Ayer Road #2
SiO <sub>2</sub>	77.45(0.62)	77.43(0.37)	77.22(0.41)	76.35(0.22)	76.98(0.20)
Al <sub>2</sub> O <sub>3</sub>	13.18(0.39)	12.74(0.19)	13.25(0.27)	13.72(0.08)	13.69(0.09)
Fe <sub>2</sub> O <sub>3</sub>	1.23(0.08)	1.15(0.09)	1.24(0.06)	1.38(0.08)	1.04(0.08)
TiO <sub>2</sub>	0.16(0.02)	0.21(0.03)	0.17(0.02)	0.14(0.02)	0.10(0.04)
Na <sub>2</sub> O	3.85(0.13)	3.51(0.14)	3.98(0.11)	4.10(0.12)	3.85(0.11)
K <sub>2</sub> O	2.29(0.09)	3.13(0.19)	2.32(0.07)	2.25(0.05)	2.38(0.09)
MgO	0.29(0.03)	0.27(0.03)	0.28(0.03)	0.32(0.03)	0.26(0.03)
CaO	1.41(0.18)	1.34(0.14)	1.45(0.09)	1.65(0.05)	1.65(0.09)
Cl	0.11(0.02)	0.19(0.02)	0.09(0.02)	0.09(0.02)	0.06(0.02)
SC	0.973	0.970	0.98	0.986	0.98
No. shards	17	16	16	26	22
Source	MSH So	GP	MSH So	MSH So	MSH C
Age	13 350	11 600	13 350	13 350	47 000

MSH, Mount St Helens; GP, Glacier Peak. Age given in <sup>14</sup>C yr BP (MSH set S: Clague *et al.*, 2003; MSH set C: Negrini *et al.*, 2000; GP: Kuehn *et al.*, 2009). Similarity coefficient after Borchardt *et al.* (1972).

tephra) is of unknown source and age (Busacca *et al.*, 1992).

The Ayer Road section is interpreted as a succession of loess, the deposition of which periodically slowed down or ceased and allowed development of calcic B soil horizons. According to Busacca & McDonald (1994), the L-1 and L-2 loess units had a source in catastrophic outburst flood deposits of late Wisconsinan (Missoula Flood) and middle or early Wisconsinan age, respectively. These loess units originated as

slackwater sediments deposited in the Pasco Basin and Walla Walla Valley.

Fossil gastropod molluscs in the Ayer Road section occur in a mica-rich interval below the Old Maid Coulee soil and the MSH set C tephra, near the base of the L-2 loess unit (Busacca & McDonald, 1994). The molluscan fauna here consists of abundant specimens of the genus *Columella* Westerlund. The occurrence of the fossils in an interval of structureless silt interpreted as loess raises the possibility that the

fossils were transported to this locality by aeolian processes. However, most of the specimens are whole and appear to be unabraded (Fig. 3B).

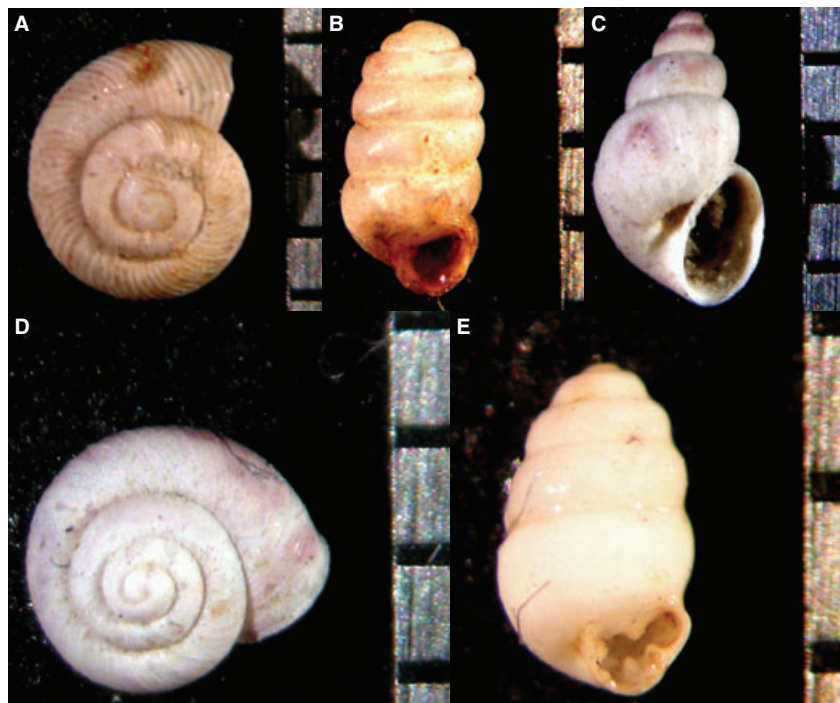
Ecological preferences of living species of *Columella* suggest that the fossils inhabited cool, moist habitats on the edges of low-lying swamps or ponds (Taft, 1961). Modern topography, as well as the geometry of the Washtucna and Old Maid Coulee soils, which mirror ancient topography, suggests that the Ayer Road section was a topographic high when the sediments accumulated. The fossil occurrence in aeolian sediment on a topographic high, in association with a calcic B-horizon soil is thus inconsistent with modern ecological preferences, lending support to the idea of a wind-transported fauna.

### McFeely Road section

Sedimentology of the McFeely Road section (Figs 1 and 2) is more complex than that of the Ayer Road site. The section is about 5 m thick and comprises rhythmically bedded fine-grained sediment with oxidized, root cast-bearing horizons and coarse-grained, small-channel deposits, containing basalt and caliche fragments, which are exposed at an elevation of about 311 m. Overlying these sediments are fine-grained sand and silt deposits containing a well-developed carbonate palaeosol. The base of the exposed section at McFeely Road

comprises rhythmically deposited fine-grained sediments. The lower contact of the McFeely Road section is not exposed. However, a few tens of metres north of the study section, rocks belonging to the CRBG are exposed in road cuts. It is likely that the base of the stratified sediments exposed in the road cut is close to the sediment/basalt contact. Two tephras (Fig. 2) occur in the McFeely Road section. The lowermost tephra is identified as the MSH So, which occurs just below the base of a mottled brown and grey, partially oxidized interval with abundant root casts overlying a set of graded beds. The upper tephra, identified as Glacier Peak, occurs within the fine-grained sediment near the top of the section.

The McFeely Road outcrop is interpreted as representing sediment that accumulated as a result of repetitive processes in an aqueous environment. Cyclicity is demonstrated in the thinly bedded silts and clays comprising the lower and middle portion of the section. The rhythmically bedded sands, silts and clays in the lower and middle parts of the section are capped by a 1 m thick unit of massive silt and clay interpreted as a soil zone. The soil is characterized by the presence of clay-rich sediment containing root casts and veinlets of oxidized material; it is morphologically similar to hydromorphic soils, as described by Duchaufour (1982), which are reduced as a result of long-term



**Fig. 3.** Representative gastropod molluscs from Ayer Road, McFeely Road, Piper Canyon and Donnelly Road study sections. (A) *Striatura*; (B) *Columella*; (C) *Succinea*; (D) *Vallonia*; (E) *Vertigo*. The scale to the right of each specimen is in millimetres.

waterlogging and absence of oxygen, but may contain segregated iron oxides resulting from aeration by root activity.

Soil in the McFeely Road section developed under moist, semi-saturated conditions, in contrast to soils in the Ayer Road section, which are calcium carbonate-rich caliche soils that formed under drier, well-drained conditions. Absence of stratification in the McFeely Road soil zone is indicative of intense bioturbation, consistent with the presence of abundant root casts. The development of a hydromorphic soil zone indicates a low rate, or periodic process of sediment deposition, and aeration of the surface sediment under saturated conditions; it may indicate infilling of a pond with sediment and concurrent growth of vegetation on the boggy soil surface. The McFeely Road section is fossiliferous, yielding abundant mollusc and rare, unidentifiable small mammal fossils. The molluscan fauna (Fig. 3) comprises five genera of gastropods, including *Columella* Westerlund, *Vertigo* Muller, *Succinea* Draparnaud, *Striatura* Morse and *Vallonia* Sterki.

The McFeely Road outcrop is interpreted as representing distal late-Missoula Flood slack-water deposits and a minor impoundment in an ephemeral stream valley that received periodic sediment input. Rhythmically graded beds of fine-grained sediment represent short-term fluctuation in depositional energy; it will be shown that these rhythmically bedded sediments are associated with the late Wisconsinan Missoula Floods. Capping this interval, an oxidized and bioturbated soil with a well-developed fauna of terrestrial gastropods suggests periods of little or no sediment input, persistence of swampy conditions, growth of vegetation and soil formation.

### Donnelly Road section

The Donnelly Road section is exposed poorly in a 1 m high roadcut between McFeely Road and Piper Canyon, at an elevation of 310 to 315 m (Figs 1 and 2). The sediments are similar in appearance and texture to the exposures in Piper Canyon. However, there are no marker tephra horizons in the Donnelly Road exposure. A single specimen of the gastropod genus *Succinea* has been recovered from the Donnelly Road section.

### Piper Canyon section

The Piper Canyon section is exposed in low roadcuts along Piper Canyon Road at an elevation of about 310 m (Figs 1 and 2). The outcrop

comprises a medium to dark grey-brown silt; sedimentary structures are not evident. In one of the exposures, a dispersed tephra is preserved which is a compositional match for MSH So (Table 1). The Piper Canyon section is interpreted as representing an environment similar to that of the hydromorphic soil zone in the McFeely Road section. The absence of stratification (other than the tephra horizon) is attributed to bioturbation of sediments. The Piper Canyon section is fossiliferous, containing abundant specimens of the gastropod genera *Columella*, *Striatura*, *Vallonia*, and *Succinea* (Fig. 3) and rare specimens of an unidentified bivalve mollusc.

## AGE AND CORRELATION OF STUDY SECTIONS

### Tephra age discrepancies

A key element in the interpretation of the study sections is the age of the MSH tephra, on which the age of the Missoula Flood sequence is based. There is considerable uncertainty on this issue; key papers in the ongoing discussion of tephra ages include Mullineaux *et al.* (1975, 1978), Crandell *et al.* (1981), Mehringer *et al.* (1984), Mullineaux (1986), Berger & Busacca (1995), Mullineaux (1996), Negrini *et al.* (2000), Clague *et al.* (2003) and Kuehn *et al.* (2009). In particular, the ages of the MSH set S ash couplet (So and Sg) are critical. The MSH set S tephra in the study sections is a close match with the So tephra (Table 1; SC = 0.98). In the following discussions, ages are in thousands of  $^{14}\text{C}$  yr BP unless otherwise stated in the text.

According to Mullineaux *et al.* (1975), the MSH set S tephra were erupted during a lengthy period of explosive activity that extended from about 18.0 to about 12.0 ka. Individual ages of the set S tephra are less certain; the So and Sg were thought to be about 13.0 kyr (Mullineaux *et al.*, 1978). In a palaeomagnetic study of Missoula Flood slackwater sediments in the Yakima and Walla Walla Valleys, Clague *et al.* (2003) indicate that the ages of the So and Sg tephra are 13.35 and 14.4 kyr, respectively.

Berger & Busacca (1995) give an age for the set S tephra of 17.0 to 21.0 kyr based on thermoluminescence (TL) dating of loess bracketing the tephra layers. This age is considerably older than all recent references to the age of the set S tephra; however, it does not seem to have been accepted widely. The age of 13.35 kyr (Clague *et al.*, 2003)

for the MSH So tephra is most consistent with the radiocarbon age of fossils and stratigraphy in the study sections.

The MSH set C tephras were erupted over an interval of 36.0 to >42.0 ka (Crandell *et al.*, 1981). According to Berger & Busacca (1995), the TL age of the MSH Cw is 46.0 ± 6 to <75.0 ± 6 kyr, based on analysis of bracketing loess; these authors further indicate a TL age of 46.0 ± 5 kyr for silt-sized glass from an MSH Cy bed in Oregon and Negrini *et al.* (2000) report an age of 47 ± 2 kyr for MSH Cy at Summer Lake, Oregon. The present study will use the age of 47 ± 2 kyr for the MSH set C tephra (Negrini *et al.*, 2000) in the Ayer Road section; the interpretation of depositional history is not contingent upon the specific identity of the set C tephra, nor on its precise age.

The Glacier Peak tephra was assigned an age of 11.2 kyr (Mehring *et al.*, 1984). More recent and comprehensive work by Kuehn *et al.* (2009) gives a revised age for the Glacier Peak tephra of 11.6 kyr. This age is consistent with the stratigraphy of the McFeely Road section of this report, in which the Glacier Peak tephra occurs in massive silt, interpreted as loess, stratigraphically above what will subsequently be shown to be Missoula Flood slackwater sediments.

**Age and correlation of study sections**

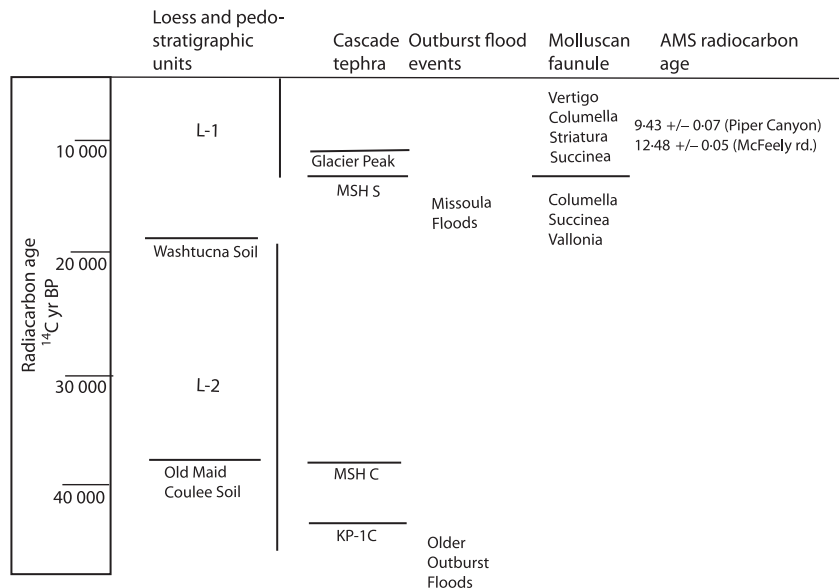
The age of the fossil-bearing outcrops is constrained to the late Pleistocene (>47.0 to 9.43 ka) as determined by geochemical characterization of Cascade-sourced tephras exposed in the sections

(Table 1) and AMS radiocarbon dating of fossil material in the McFeely Road and Piper Canyon sections. Correlation of study sections to the pedostratigraphic scheme established by Busacca & McDonald (1994) and tephra chronology are shown in Figs 2 and 4.

The Ayer Road section contains tephra from Mt St Helens set C (ca. 47.0 ka; Negrini *et al.*, 2000) and So (ca. 13.35 ka; Clague *et al.*, 2003). The fossiliferous interval occurs below the set C horizon and the Washtucna and Old Maid Coulee soils (Figs 2 and 4); this interval represents the lower part of loess unit L-2 (Busacca & McDonald, 1994). The presence of the MSH So tephra in the upper part of the section indicates that at least a part of the L-1 loess is present.

The McFeely Road section contains tephra from MSH So (13.35 kyr; Clague *et al.*, 2003) and Glacier Peak (11.6 kyr; Kuehn *et al.*, 2009). Accelerator mass spectrometry radiocarbon dating of fossil material from McFeely Road establishes the age of the fauna as 12.48 ± 0.06 kyr; specimens taken for dating are from a well-developed soil zone above the So tephra. The So tephra and the fossiliferous part of the section occur about 3 to 4 m above the base of the exposure; this section spans the boundary between loess units L-2 and L-1 of Busacca & McDonald (1994). The soil from which the dated fossil specimens are taken post-dates the last Missoula Flood. Stratigraphic relationships and ages are shown in Figs 2 and 4.

The Piper Canyon section yielded an AMS radiocarbon age from specimens above the tephra of 9.43 ± 0.05 kyr, and is loosely correlative with



**Fig. 4.** Relationship between loess and pedostratigraphic units, tephra horizons, outburst flood sequences, molluscan faunules and radiocarbon age for outcrops discussed in the text. No scale intended.

the fossil-bearing interval at McFeely Road. The tephra exposed in the Piper Canyon section is the MSH So based on similarity in sediment type, similar inferred stratigraphic position, tephra glass composition (Table 1) and the radiocarbon age of the fossils associated with the tephra in outcrop.

The Ayer Road, McFeely Road, Donnelly Road and Piper Canyon sections overlap in time and are correlative with sections studied by Busacca *et al.* (1992) (Figs 2 and 4) representing the L-1 and L-2 loess units. The correlations are significant when viewed in the context of the sedimentological interpretations. The Ayer Road section represents a long period of loess aggradation interrupted at intervals by topographic stability and soil development. In part concurrent with this, the McFeely Road and Piper Canyon sections were accumulating sediment under aqueous conditions.

## RELATIONSHIP OF STUDY SECTIONS TO MISSOULA FLOOD DEPOSITS

The late Pleistocene Missoula Floods resulted from repeated catastrophic failure of an ice dam on Clark's Fork west of Missoula, Montana. During the last-glacial episode of flooding there were as many as 40 individual flood events (Waite, 1980, 1985). Each flood carried a heavy load of sediment ranging in grain-size from coarse sand to silt; in addition, the flood waters carried sediment-laden ice bergs. Deposits related to the Missoula Floods in the study area are characterized as slackwater facies laid down as floodwaters backed up at the constriction formed by Wallula Gap and back-flooded the Pasco Basin and Walla Walla Valley (Fig. 1). The slackwater deposits in the Walla Walla Valley are known as the Touchet Beds (Flint, 1938). Thickness relationships in well-exposed sections of the Touchet Beds suggest that the flood events later in the Missoula Flood sequence were of greater frequency and lesser magnitude than were the earlier floods (Waite, 1994).

The maximum elevation of flood waters was 381 m at Wallula Gap (Fig. 1) based on the presence of deposits of cobble and boulder erratics carried by glacial ice, which became stranded on the shoreline as flood water receded (Allen *et al.*, 1986). That elevation represents maximum flood elevation at the point of constriction at Wallula Gap. It is likely that later floods only reached lower elevations (based on the work of Waite, 1994) more consistent with the elevation of

stratified sediments and soils at McFeely Road, Donnelly Road and Piper Canyon.

The precise timing of the Missoula Floods is a subject on which there is still some discussion, and it hinges largely on the age of the MSH So and Sg tephra couplet. Benito & O'Conner (2003) indicate that several of the Missoula Floods post-date the set S tephra; the Missoula Floods are generally thought to have taken place between about 15.0 <sup>14</sup>C ka and the end of glacial Lake Missoula at about 12.7 <sup>14</sup>C ka. Whatever the age of the latest Missoula flood, it is well-documented that the MSH set S tephra occur at least several beds below the top of the Missoula Flood sequence (Waite, 1980, 1985).

In the Walla Walla River drainage, valleys tributary to the Walla Walla River were back-flooded to elevations consistent with maximum flood elevations at Wallula Gap and elsewhere in the Walla Walla Valley. Exposures of the Touchet Beds in the study area show that the top of the sequence lies at an elevation of less than about 320 m. Floods sufficient to deposit Touchet Beds at these elevations would backflood the McFeely Road, Donnelly Road and Piper Canyon areas to elevations consistent with those of the stratified and soil-bearing units.

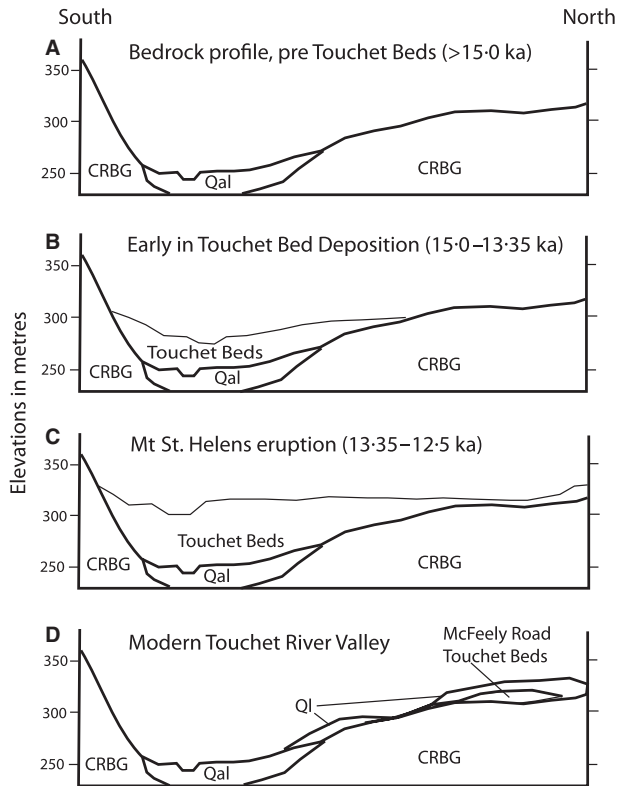
## Interpretive depositional history: Touchet River Valley and McFeely Road

The following scenario for deposition of sediments in the McFeely Road, Donnelly Road and Piper Canyon sections is based on the radiocarbon age of the molluscan fauna, geochemical identity and age of preserved tephra, present-day elevations of the outcrops, and the presence of Missoula Flood slackwater deposits along the sides of the Touchet River Valley at elevations similar to the study sections. The series of interpretive cross-sections shown in Fig. 5 diagrammatically represents the evolution of the Touchet River Valley at McFeely Road; a similar evolution is inferred for correlative outcrops at Donnelly Road and Piper Canyon.

### *Stage 1 (>15.0 ka)*

Prior to initiation of the late Wisconsinan Missoula Floods, the Touchet River Valley was flooded by alluvium deposited on the floodplain of the ancestral Touchet River. Rocks belonging to the CRBG were exposed in the valley walls. At this stage, there may have been a thin covering of loess on parts of the exposed basalt surface (loess unit L-2 of Busacca & McDonald,





**Fig. 5.** Evolution of Touchet River Valley and the McFeely Road section during the late Pleistocene. CRBG, Columbia River Basalt Group; Qal, Touchet River alluvium; Ql, Quaternary loess. See text for explanation. Elevation is in metres.

1994), although there is no record of this unit in the McFeely Road exposure. To the west, the Ayer Road outcrop does preserve this older loess unit (Fig. 5A).

#### *Stage 2 (between 15.0 and 13.35 ka)*

At some point of time early in the Missoula Flood sequence, but prior to the MSH So eruption, the valley was partially filled with slackwater sediments. The floods scoured any loess from higher elevation basalt surfaces, and redeposited the sediments as part of the slackwater facies. Subsequent to each event of flooding, normal fluvial processes resumed and the Touchet River regraded its floodplain, redistributing slackwater sediments and downcutting portions of the floodplain. Fluvial activity in the ephemeral stream that periodically occupied the McFeely drainage eroded Missoula Flood sediments deposited at higher elevations. Any loess accumulating during the interflood periods was minimal, as individual flood events were separated by only decades (Waite, 1985) (Fig. 5B).

#### *Stage 3 (13.35 to 12.5 ka)*

By the time of the eruption of the MSH So tephra, the valley had received a blanket of slackwater sediment that partially covered the McFeely drainage to an elevation of at least 315 m. The Touchet River partially regraded the floodplain, but the extent of the sediment blanket prevented complete removal of Missoula Flood sediment at the highest elevations in the McFeely drainage. Mount St Helens So tephra blanketed the region as a thin but relatively pure layer. The stratified sediment at the base of the McFeely Road section represents the upper limit of deposition during the latest phase of flooding of the Missoula Flood sequence.

The deposition of slackwater sediment far up the McFeely drainage flattened the gradient on the ephemeral stream, and allowed water in the drainage to pond on the irregular surface of the Missoula Flood deposits. Locally, this surface allowed sediment washed from higher elevations to accumulate in topographic lows and keep the surface saturated. Slopewash from exposed basalt surfaces on the McFeely valley walls generated the small-scale, coarse-grained channel-fill deposits in the exposure. Hydromorphic soils formed on the surface of these saturated low spots here, and in the Piper Canyon and Donnelly Road exposures, over the next few thousand years (Fig. 5C).

#### *Stage 4 (11.6 to 9.43 ka)*

Subsequent to the final event in the Missoula Flood sequence, erosion of the higher elevations on the valley sides removed much of the accumulated slackwater sediment and the associated soils. This effect was accomplished in large part by regrading of the floodplain by the Touchet River but was aided by stream flow in the McFeely drainage and slopewash processes. The final few Missoula Floods may have played a role in scouring earlier flood deposits from the valley sides. However, it is also possible that the final few Missoula Floods were of insufficient magnitude to flood the valleys to the elevation of the McFeely Road and correlative sections. Removal of the soils and rhythmically deposited sediments (now the McFeely Road, Donnelly Road and Piper Canyon outcrops) was incomplete. After the Missoula Floods, deposition of loess unit L-1 commenced and the region, including the study sections, was covered with a discontinuous blanket of aeolian sediment. Glacier Peak erupted the 11.6 kyr tephra. The Touchet River regraded its floodplain to the current elevation (Fig. 5D).

## THE FAUNA AND ITS POTENTIAL PALAEOECOLOGICAL AND BIOSTRATIGRAPHIC SIGNIFICANCE

The fauna preserved in the study sections comprises five genera of gastropods previously undocumented from sediments of late Pleistocene age in south-eastern Washington. All taxa are represented by living species elsewhere in the Pacific Northwest and the mid-western USA; fossils of similar species are known from deposits of a similar age in the mid-west (Wayne, 1959; Taft, 1961; Branson, 1980; Karrow *et al.*, 1997). Representative specimens are illustrated in Fig. 3.

Snail faunas provide useful palaeoenvironmental data which, in combination with mammalian fossils and other physical and biological criteria, establish a firmer basis for palaeoenvironmental interpretation of the region during the time period in question. In the Pleistocene of Indiana, species of *Columella*, *Vertigo* and *Succinea* occurring in Wisconsinan and pre-Wisconsinan silts, loess and lake sediment suggest cool-to-cold, moist, open-park conditions (Wayne, 1959). Living specimens of *Vertigo* in the Washington Cascades are found in close proximity to active glaciers and recently deglaciated valleys at elevations in excess of 1000 m (Branson, 1980). The fossil specimens from the study sections can be inferred to represent similar conditions of cool-to-cold, moist, open-park habitat. This observation is consistent with inferred climatic conditions in the region as the Cordilleran ice sheet began its most recent advance into Washington about 25.0 ka and the final retreat sometime around 14.0 ka (Clague *et al.*, 1980).

Stratigraphic distribution of the fossil species indicates that there are two faunules present. In the McFeely Road section, occurring beneath the MSH So tephra and representing the lower portion of loess unit L-1, a faunule composed of *Vallonia*, *Columella* and *Succinea* is preserved. Above the So tephra, a faunule composed of *Succinea*, *Striatura*, *Columella* and *Vertigo* is preserved. *Striatura* and *Vertigo* have not been recovered from sediments below the MSH So tephra. In the Piper Canyon section, the fauna above the So tephra is composed of *Columella*, *Striatura* and *Succinea*. *Vertigo* has not been found. In the Donnelly Road exposure, a single specimen of *Striatura* has been recovered from the poorly exposed outcrop. Analysis of the snail faunules shows the genera *Vertigo* and *Striatura* only occurring above the MSH So tephra, in sediments corresponding to loess unit L-1 of

Busacca & McDonald (1994), while *Vallonia* only occurs below the So tephra. The relationship of faunules to pedostratigraphic units, tephtras and the study sections is summarized in Fig. 4.

## CONCLUSIONS

Stratigraphic and sedimentological analysis of the study sites indicates that the informally recognized Palouse loess in the southern part of the Columbia Basin comprises a more diverse assemblage of sedimentary facies than has been recognized previously. These facies include aeolian, fluvial and lacustrine sediments and iron-rich soils associated with slackwater deposition by the late Wisconsinan Missoula Floods in distal tributary valleys of the Walla Walla River in south-eastern Washington, which were backflooded during the late Pleistocene outburst flood events.

Stratigraphic control in the study sections is provided by the presence of distinctive pedostratigraphic units (Washtucna and Old Maid Coulee soils), geochemical identity of Cascade-sourced tephtras (Mount St Helens So, *ca* 13.35 kyr; set C, *ca* 47.0 kyr; and Glacier Peak, *ca* 11.6 kyr) and accelerator mass spectrometry radiocarbon dating of snails from exposures at McFeely Road and Piper Canyon (ages 12.48 and 9.43 kyr, respectively). Study sections comprise parts of loess units L-1 and L-2 in the scheme developed by Busacca & McDonald (1994).

Fossil gastropods collected from late Pleistocene aeolian and fluvio-lacustrine sediments in south-eastern Washington represent the first published report of land snails from the late Pleistocene Palouse loess. The stratigraphic distribution of these fossils is in sediments ranging in age from >47.0 to 9.43 ka, within the L-1 and L-2 loess units. The fossils define two distinct faunules; the boundary between them is the Mount St Helens So tephtra. Similar species occur in Pleistocene loess and related deposits in the mid-western USA; similar living species are found in alpine and sub-alpine valleys in the Cascade Mountains of Washington. The gastropod fauna suggests conditions of cool-to-cold, moist, open-park conditions for this part of south-eastern Washington for the latest Pleistocene, which is consistent with the presence of continental ice to the north during at least part of the time period represented in the study sections. These faunules, together with the soil and tephtra horizons, provide a means for establishing ages and relative stratigraphic positions, as well as palaeoenvironmental

reconstructions, within the late Quaternary loess of the Pacific Northwest.

The radiocarbon age of the fossil material associated with the Mount St Helens So tephra helps to resolve discrepancies in the reported ages of this tephra in the published literature. Published ages range from as young as 12·0 to as old as 21·0 kyr based on radiocarbon and thermoluminescence dating. This study shows a fossil fauna in the McFeely Road section that is associated closely with, and above, the Mount St Helens So tephra as having an age of  $12\cdot48 \pm 0\cdot06$  kyr. The age of the So tephra (13·35 kyr) as given by Clague *et al.* (2003) is probably accurate.

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