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Frost Action during the Younger Dryas Inferred from Soil Micromorphology at Connley Cave 5, Oregon

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1. Introduction

The Younger Dryas chronozone (hereafter "YD") is an abrupt climate event occurring between ~12,900–11,700 calendar years ago (cal yr BP) or ca. 11,000–10,000 ^{14}C yr BP (Alley et al. 1993; Broecker et al. 2010; Cheng et al. 2020; Smith et al. 2020). In Western North America's Great Basin region, the YD is marked by rapid cooling which co-occurs with the decline of multiple genera of megafauna (Grayson 2016), pluvial lake-level fluctuations (Adams et al. 2008; Benson et al. 1990; Currey 1990; Reheis et al. 2014), shifts in vegetation types (Beck, Bryant, and Jenkins 2018; Goebel et al. 2011; Minckley, Bartlein, and Shinker 2004), and the earliest widespread archaeological record in the region – the Western Stemmed Tradition (WST) (Beck and Jones 2010; Bryan 1980; Davis, Willis, and Macfarlan 2012; Smith et al. 2020; Smith and Barker 2017). Renewed research efforts over the last decade, including sustained excavations and targeted studies applying novel analytical techniques, have identified around 10 sites with buried deposits dating to the YD (Figure 1(a); e.g., Blong et al. 2020; Connolly et al. 2017; Duke et al. 2022; Goebel et al. 2011; 2021; McDonough et al. 2022; Jenkins et al. 2012; 2016; Jenkins, Holcomb, and McDonough 2017; Rosencrance 2019; Rosencrance et al. 2019; Shillito et al. 2018; 2020; Smith et al. 2020). As a result, Great Basin archaeologists working at these sites have begun to contribute new data to better evaluate human-environment dynamics during the Late Pleistocene to Early Holocene transition (LP/EH). This includes research seeking to reconstruct paleoenvironments since the last deglaciation, especially pluvial lake-level and vegetation histories at key archaeological sites (Adams et al. 2008; Beck, Bryant, and Jenkins 2018; Hudson et al. 2021; Kallenbach 2023; Saban et al. 2023), understand

Paleoindian subsistence (Blong et al. 2020; Hockett et al. 2017; McDonough et al. 2022), and evaluate the relationship between Paleoindian land-use, foraging strategies, and technological organization (Bradley, Smith, and Nussear 2022; Reaux 2021; 2022; Reaux et al. 2018; Smith 2010; Smith et al. 2015; Smith and Harvey 2018; Smith, Middleton, and Carey 2013*)*.

Figure 1 *(a) Great Basin archaeological sites with contexts dating to the Younger Dryas including: (1) Connley Caves, (2) Cougar Mountain Caves, (3) Paisley Caves, (4) Weed Lake Ditch, (5) Tule Lake Rockshelter, (6) Last Supper Cave, (7) Danger Cave, (8) Bonneville Estates Rockshelter, (9) Wishbone Site, and (10) Smith Creek Cave; (b) photo of Connley Caves 3–6 facing north; (c) plan view of Connley Cave 5 excavation and units; (d) photo of completed excavations as of 2019 (Unit 20 is the profile sampled in this study).*

A recurring theme in Great Basin archaeology is that most stratified Pleistocene-aged archaeological sites are found preserved within cave and rockshelter settings (Figure 1(a)) (Smith et al. 2020). Several researchers have raised the point that this has biased our understanding of past human lifeways (Jamaldin 2018; Smith et al. 2020). However, another issue is that despite having favorable preservation conditions for organics (e.g., osseous and fiber technologies), caves and rockshelters also preserve contexts formed by fine-grained processes sometimes difficult to tease apart with the naked eye alone, an issue that is exacerbated by the many forms of post-depositional disturbances typical in these settings (Goldberg and Sherwood 2006). To address these issues, geoarchaeologists turn to the micro-scale (< 2 mm), taking advantage of a multitude of analytical techniques capable of assessing the stratigraphic integrity of deposits and higher resolutions, recording organic and inorganic sediment and soil compositions in more detail, and identifying "geo-indicators" of climate variability and their effects on archaeological assemblages (Goldberg and Berna 2010; Goldberg and Sherwood 2006; Karkanas and Goldberg 2013; Shillito et al. 2018; Weiner 2010). One analytical technique that has proved crucial for controlling micro-contextual concerns during excavation is soil and sediment micromorphology – the microscopic study of the arrangement, composition, and life-history of undisturbed sediments and soils (Courty, Goldberg, and Macphail 1989; Karkanas and Goldberg 2018; Macphail and Goldberg 2018).

Recent research at Connley Caves (35LK50), located in the Fort Rock Basin of Oregon, has revealed well-stratified sediments and soils preserving WST assemblages spanning the YD to Early Holocene, offering a unique opportunity to study YD-aged sediments preserved within cave and rockshelter settings (Jenkins, Holcomb, and McDonough 2017; McDonough et al. 2022; Rosencrance et al. 2022). In this paper, we apply soil micromorphology at Connley Cave 5 to achieve four research objectives: (1) evaluate site formation processes occurring across the LP/EH boundary; (2) understand the degree of stratigraphic integrity of the earliest deposits at the site; (3) shed light on the paleoenvironmental context of Connley Caves; and (4) understand how these data facilitate a better understanding of Pleistocene archaeology in the Great Basin.

2. Background

2.1. Study area: Connley Caves, Oregon

Connley Caves represent a series of eight rockshelters situated in the south-facing slope of the Connley Hills – a volcanic tuff and rhyolite ridge separating the Fort Rock and Silver Lake sub-basins (Figure 1(b); Freidel 1993; Jenkins et al. 2004). The shelters were formed by lake-level fluctuations of pluvial Fort Rock Lake, which preferentially eroded areas of structural weakness (i.e., fault zones) within the volcanic bedrock. After the lake receded from the shelters, sometime before ~11,100 ^{14}C yr BP, around 4 m of well-stratified sediments and cultural materials spanning the Late Pleistocene and Holocene were deposited into the cave.

Stephen Bedwell's excavations at Connley Caves in 1968 and 1969 yielded artifacts and radiocarbon dates spanning the last 13,000 years (Bedwell 1973; Rosencrance et al. 2022); however, concerns about the reliability of the radiocarbon chronology endured (Bryan 1980; Goebel et al. 2011; Grayson 1979). The University of Oregon's Museum of Natural and Cultural History Archaeology Field School returned to Connley Caves between 2000–2001 and 2014–2023 to refine the chronological, ecological, and technological records (Jenkins, Holcomb, and McDonough 2017; McDonough et al. 2018; 2022; Rosencrance et al. 2022). Those excavations revealed well-stratified sediments with buried cultural components reflecting people's intermittent visits to the shelters going back at least 12,500 years (McDonough et al. 2022). Connley Caves is a multicomponent site with archaeological assemblages that span from the Pleistocene to the nineteenth century. Cultural material in the LP/EH deposits of Connley Cave 5 include multiple stratified cultural assemblages characterized by toolkits with WST points, eyed bone needles, gravers, scrapers, and expedient tools (McDonough et al. 2022). Analysis of these assemblages is ongoing, but McDonough et al. (2022) provide a summary of primary cultural components and Table 1 presents radiocarbon ages.

Table 1 Radiocarbon dates from Connley Caves.

Cave	LU	^{14}C date	95.4% probability	Lab number	Material dated	Reference
5	5	7770 ± 45*	8635–8425	D-AMS 24522	*Artemisia* charcoal	This study
5	5	7950 ± 40	8985–8640	Beta-146867	*Artemisia* charcoal	Beck et al. (2004)
5	5	8140 ± 40*	9265–8995	D-AMS 23354	*Artemisia* charcoal	This study
5	5	9050 ± 30*	10,245–10,185	PSUAMS#5246	*Artemisia* charcoal	McDonough et al. (2022)
5	5	9170 ± 40*	10,490–10,235	D-AMS 24523	*Artemisia* charcoal	McDonough et al. (2022)
5	4b	9985 ± 35*	11,690–11,265	PSUAMS#5007	*Artemisia* charcoal	McDonough et al. (2022)

Cave	LU	^{14}C date	95.4% probability	Lab number	Material dated	Reference
5	4b	10,010 ± 50*	11,735–11,275	D-AMS 30300	*Artemisia* charcoal	McDonough et al. (2022)
5	4b	10,030 ± 95*	11,875–11,245	D-AMS 30298	*Artemisia* charcoal	McDonough et al. (2022)
5	4b	10,115 ± 50*	11,935–11,400	D-AMS 30299	*Artemisia* charcoal	McDonough et al. (2022)
5	4b	10,120 ± 35*	11,930–11405	PSUAMS#5008	*Artemisia* charcoal	McDonough et al. (2022)
5	4b	10,150 ± 40*	11,940–11,505	PSUAMS#7103	*Artemisia* charcoal	McDonough et al. (2022)
5	4b	10,190 ± 35*	11,970–11,735	PSUAMS#5009	*Artemisia* charcoal	McDonough et al. (2022)
5	4b	10,275 ± 35*	12,435–11,820	PSUAMS#6712	*Artemisia* charcoal	McDonough et al. (2022)
5	4b	10,290 ± 35*	12,450–11,830	PSUAMS#7104	*Artemisia* charcoal	McDonough et al. (2022)
5	4a	10,420 ± 35*	12,595–12,095	PSUAMS#6715	*Artemisia* charcoal	McDonough et al. (2022)
5	4a	10,490 ± 35*	12,625–12,195	PSUAMS#6714	*Artemisia* charcoal	McDonough et al. (2022)
5	4a	10,560 ± 35*	12,690–12,480	PSUAMS#6716	*Artemisia* charcoal	McDonough et al. (2022)
5	3	10,650 ± 35	12,730–12,615	PSUAMS#6718	*Artemisia* charcoal	This study
4	2	10,770 ± 40	12,770–12,685	D-AMS 12795	*Artemisia* charcoal	Jenkins, Holcomb, and McDonough (2017)
4	2	10,930 ± 40	12,955–12,785	D-AMS 12790	*Pinus* charcoal	Jenkins, Holcomb, and McDonough (2017)
4	2	11,060 ± 40	13,050–12,855	D-AMS 12792	*Salix* charcoal	Jenkins, Holcomb, and McDonough (2017)
4	2	11,105 ± 45	13,105-12,900	D-AMS 24921	*Artemisia* charcoal	Rosencrance et al. (2022)

* = derived from feature (i.e., hearth or combustion area).

2.2. Identifying frost action at the micro-scale

Frost action occurs under conditions of seasonal and longer-term freezing in cold climate regimes in high altitude and latitude regions around the world today, or in the past during periods of cold domain extension during the Quaternary where the yearly mean temperature is below 0º C (i.e., glacial periods or stades) (Kimble 2004). Frost serves as a pedogenic agent through temperature-driven soil desiccation, ice lensing, and ice segregation which results in diagnostic features preserved within soils and sediments (Van Vliet-Lanoë 1985; 1998; 2010). Archaeologists working in northern regions such as Alaska or Canada are no stranger to these features, at both the macro- and microscopic scales (DiPietro, Driese, and Goebel 2018; Kielhofer et al. 2020). Cryogenic features at the outcrop scale include stratigraphic inversions and injection features, such as frost wedges. To our knowledge, such features have not been observed throughout the Great Basin, though they have been observed on the Columbia Plateau at Owl Cave (Wasden Site) in Idaho (Butler 1963; Henrikson et al. 2017). As we demonstrate here, even though these features are difficult to identify in the field-setting, that does not mean that they are not occurring at the microscopic scale.

Understanding the effects of frost action is crucial for evaluating cryoturbation, post-depositional transformation of sediments into soils (cryogenesis), and for archaeological purposes, the spatial integrity of buried archaeological assemblages. Van Vliet-Lanoë, Fox, and Gubin (2004) and Van Vliet-Lanoë (2010) provide a full review of the processes and resulting microscopic features generated by frost action in soils and sediments. These include cryogenic soil formation (structural development), translocation of fine particles during freezing and subsequent thawing (freeze–thaw cycling), and deformation of sediments and soils through swelling, desiccation, and ice segregation. Below, we provide a brief review of those cryogenic processes relevant to Connley Caves. It is important to note that identifying just one form of cryogenic feature is typically not enough to imply a major climate event due to equifinality issues but should be considered together across multiple features through the profile and within the same unit (Van Vliet-Lanoë 2010). We anticipate more cryogenic features to be identified with future research at Connley Caves but hope that these examples can aid ongoing research aiming to study YD formation processes at other sites in similar settings in the Great Basin, and potentially elsewhere.

2.2.1. Cryogenic microstructures

Intense freeze–thaw activity in periglacial environments creates diagnostic soil structures – soil aggregates (peds) bonded together to form characteristic morphologies (Birkeland 1999; Van Vliet-Lanoë 2004; 2010; Van Vliet-Lanoë, Fox, and Gubin 2004). Frost activity in theseenvironments can also create diagnostic soil structures at the micro-scale, or microstructures, through the process of segregation of ice in the soil in the form of ice lensing (Van Vliet-Lanoë 2004). The expansion of water when it transforms to ice causes an increase in soil volume, and subsequent freezing and thawing cycles over time results in varying degrees of displacement within the soil matrix, resulting in characteristic morphologies capable of study (Tedrow 2004).

Perhaps the most diagnostic microstructure is the isobanded or banded fabric (McMillan and Mitchell 1953). Development and subsequent detraction of ice lenses during thawing creates smooth planar fissures with unconforming boundaries which delimit platy or lenticular ped structure (Van Vliet-Lanoë 1985). The translocation of fine particles (i.e., silt) down profile during thawing results in diagnostic silt caps, which over time and with multiple cycles, will overlap to become banded fabrics. These banded fabrics form if silt is moist but not saturated, and lenticular structures typically form closer to the soil surface while angular blocky structures (in clay textures) form deeper within the profile (Van Vliet-Lanoë 2010). Lenticular peds can become rounded if the underlying bedrock is sloped, causing a slow mass movement process called frost creep. As noted below, slow downslope mass movement of soil will result in a characteristic silt coating on multiple surfaces of coarse clasts as silt caps form on rotating clasts.

Another dominant microstructure typical of frost-affected soils are vesicular structures, which are formed from the rapid thawing and subsequent expulsion of trapped air during the collapse of banded fabrics (Van Vliet-Lanoë 2010). Vesicular microstructures are characterized by rounded and mammilated pores or vesicles throughout the matrix. It should be noted that platy microstructures in the form of linear voids can form through compaction via trampling (see Holcomb and Karkanas 2019, figure 1(d)), while vesicular structures have also been found in puddled layers of paddied soils (Stoops 2021, 71) and within vesicular Av horizons associated with desert and arctic hyper arid environments (Birkeland 1999, 13).

2.2.2. Cryoturbation and solifluction: Pedofeatures

Soils, and the archaeological assemblages contained within them, can move together as a cohesive unit (plastic deformation) in the form of differential frost heave orthogonal to the topographical surface (Van Vliet-Lanoë, Fox, and Gubin 2004). This type of disturbance can be identified in the field setting. Soils particularly susceptible to this degree of frost heave are those that are poorly drained due to increased water retention capabilities owing to clay or organic rich horizons (Vliet-Lanoë 2004). However, in situations where sedimentation outpaces pedogenesis, such as at Connley Caves, cryoturbation processes can still occur at the microscopic scale, allowing an analyst to evaluate micrometer to centimeter-scaled disturbances.

Microscopic features that occur as discrete units within soil material – referred to as pedofeatures – enable the analyst to determine the degree to which cryoturbation has affected a deposit, even if that disturbance is not observed with the naked eye (Van Vliet-Lanoë 1985). Plastic deformation of sediments and soils are related to the original sedimentary fabric of the deposit, drainage differences associated with temperature gradient (thermal conditions), frost susceptibility, and thaw response to gravity (Vliet-Lanoë 2004). During freeze–thaw cycling, the down-profile translocation of fine particles (silt) will result in silt caps, which over time, will overlap to form the characteristic banded microstructure.

2.2.3. Coarse clast deformation

Particularly important to archaeologists is the role of frost action for affecting the spatial distribution and patterning of buried coarse clasts, including rock fragments, artifacts, or ecofacts. As we demonstrate here, coarse clast vertical and lateral movements can be identified at the microscopic scale, even if they are not apparent in the field setting at the outcrop scale. At the micro-scale, this can include the vertical movement and orientation of coarse clasts due to the development of underlying ice lenses which exert pressure on clasts – a process known as frost jacking (Van Vliet-Lanoë 2010). Clasts can also move at the micro- to millimeter-scale due to cryosuction – the increased retraction and accentuated suction associated with gentle frost heave. Finally, clasts can be shattered by intense frost action, and this process can leave measurable effects on artifact assemblages (Michel, Cnuts, and Rots 2019).

3. Methods

We identified six informal lithostratigraphic units (LU) dating before the eruption of Mount Mazama (ca. 7630 cal yr BP) based on their texture, color, mineralogy, and geometry following the United States Department of Agriculture (USDA) Soil Survey nomenclature (Soil Survey Division Staff 1993) and North American Stratigraphic Code (NASC 2005) (Table 2). In this study, we targeted those units dating to the YD, including LU2–4 (Table 2). These deposits include eolian, colluvial, biogenic, anthropogenic, and *éboulis* (wall erosion), and lacustrine inputs.

Table 2 Macroscopic description of lithostratigraphic units (LU) at Connley Cave 5 (35LK50).

LU	Description	Interpretation
6	Well-sorted white (10YR 8/1) fine to coarse sand-sized lapilli (tephra). Sometimes laminated with well-preserved bedding structures fining upward. Clear smooth lower boundary.	Pyroclastic sediments (Mt. Mazama eruption)
5	Moderately to poorly sorted brown (10YR 4/3) silt with few angular cobbles and many angular gravels. Loose consistency. Occasional patches of many fine gravels. Lower boundary is erosional (abrupt and wavy).	Eolian sediments with periodic pulses of colluvium
4b	Moderately sorted brown (10YR 4/3) silt with many fine angular gravels. Gypsiferous (increase from underlying unit). Loose consistency. A lower boundary dips to the south and is clear and wavy.	Eolian sediments and éboulis
4a	Moderately sorted brown (10YR 4/3) silt with many fine angular gravels. Loose consistency.Gypsum occurs as very fine crystals on and within coarse clast fractures and discontinuously throughout matrix. Clear smooth lower boundary dips to the north.	Eolian sediments and éboulis
3	Well-sorted yellowish brown (10YR 5/4) silt with common fine angular gravels. Soft. Lower boundary appears conformable and is clear and wavy.	Eolian sediments
2	Moderately cemented yellowish brown (10YR 5/4) and brown (10YR 4/4) mottled silt with platy parting to subangular blocky structure. Moderately hard. overlapping LU1 and LU2 contact.Occasional laminations due to ice lensing. Lower boundary is conformable and abrupt and wavy.	Frost-affected buried soil on eolian sediments
1	Rounded and subrounded cobbles and gravels of mixed lithology in loose dark yellowish brown (10YR 4/4) fine sand and silt. Clast supported. Lower boundary unobserved. Freeze-thaw altered upper 10 cm.	Lacustrine sediments

We obtained foursoil micromorphology samples from LU2–LU4a, as well as one sample from Feature 3 – a rock-lined hearth within LU4b – for a total of five samples (Figure 2 and Table 3). Feature 3 (17-HF-1) is a rock-lined hearth with nine cobbles arranged in a circle within Unit 17, within which is an area of concentrated charcoal expanding into Unit 15B (see McDonough et al. 2022, figure 3). To acquire these samples, we encased undisturbed sediments from the stratigraphic column within a gypsum plaster in the field and allowed them to air dry for an hour before extraction. We then took the samples to the Malcolm H. Wiener Laboratory for Archaeological Science in Athens, Greece, where they were dried at ca. 60^{o} C for several days before being impregnated with a mixture of low viscosity polyester crystic resin, styrene monomer, and methyl ethyl ketone peroxide

(MEKP) at a ratio of 700:300:7 ml. After drying the samples for several weeks, the hardened samples were cut into chips using a rocksaw and mailed to Quality Thin-Sections in Tucson, Arizona, where they were prepared into a total of five large format (2 × 3″ or 5.08 × 7.62 cm) thin-sections for analysis. We then viewed the thin-sections under plane transmitted plane-polarized (PPL), cross-polarized (XPL), and oblique incident light (OIL) using an Olympus BX53 polarizing light microscope at magnifications between 20x to 400x at the Kansas Geological Survey. Descriptive terminology followed Stoops (2021).

Figure 2 *(a) Photograph of Unit 20 facing east; (b) stratigraphic interpretation, sampling areas, and radiocarbon chronology of Unit 20 from Connley Cave 5. Dates are uncalibrated radiocarbon ages before present (see Table 1). A fifth sample, not illustrated here, was taken from Feature 3 (but see McDonough et al. 2022, Figure 3).*

Table 3 Contextual information for five soil micromorphology samples retrieved from Connley Cave 5.

Cryogenic features	Unit observed	Formed by	Example figure
Microstructures			
Lenticular	LU2 (bottom)	Lateral rotational downslope mass movement (frost creep)	3a
Banded	LU2 (top), LU4a	Translocation of fine particles during thawing and desiccation (freeze-drying)	3b; 3c
Vesicular	LU3, LU4a, F3	Rapid thawing and water escape	3d; 3e; 3g
Pedofeatures			
Silt coating	LU2 (bottom)	As above but with lateral downslope movement (frost creep)	3a; 4a
Silt capping	LU3, LU4a, F3	Translocation of fine particles during thawing	3c; 4b; 4c;
Coarse clast deformations			
Linear voids (pores) under coarse clasts	LU2, LU3, LU4a, F3	Frost-induced moisture retraction – shrink swell (cryosuction during mild frost heaving)	3c; 4f

4. Results: Younger Dryas-induced cryogenic features at Connley Cave 5

Soil and sediment micromorphology at Connley Cave 5 revealed several key microscopic features associated with frost action, including cryogenic microstructures, pedofeatures, and coarse clast deformation, and each of these features will be discussed in detail below. While full micromorphological analysis of Connley Cave 5 is ongoing, here we provide a summary of frost action identified at Connley Cave 5 (Table 4).

Table 4 Younger Dryas-induced cryogenic and microscopic features observed at Connley Cave 5.

Sample ID	Excavation Unit	Orientation	Lithostratigraphic Unit LU)	Depth (m ASL)
CC-5-3a	20	East	2	1354.50–1354.45
CC-5-3b	20	East	3	1354.60–1354.55
CC-5-3c	20	East	4a/3	1354.70–1354.65
CC-5-4a	20	East	4a	1354.85–1354.80
CC-5-2	17	West	4a	1355.80–1355.75

At Connley Cave 5, we identified three types of microstructures diagnostic of frost-affected sediments: (1) rounded, indicated by granular peds; (2) banded fabrics, characterized by multiple silt cappings linked together across peds or coarse clasts; and (3) vesicular, indicated by common to very common rounded and mamillated vesicles. Rounded (granular) microstructures have only been identified within the lower few centimeters of LU2 (>10 cm from overlying contact) (Figure 3(a)), while banded fabrics are well-preserved throughout in the upper portionLU2 (Figure 3(b)). Banded fabrics are differentially preserved within LU4a, occasionally appearing within burrows (Figure 3(c)). Vesicular structures are common at Connley Caves, occurring within LU 3 (Figure 3(d)), LU4a (Figure 3(e)), and within YD-aged features, such as Feature 3 (Figure 3(f)).

Figure 3 *Younger Dryas-induced microstructures observed at Connley Cave 5: (a) lenticular to granular microstructure within lower part of sample CC-5-3a (yellow arrows) indicative of frost creep within LU2 (sc = silt coating); (b) banded microstructure of upper half of sample CC-5-3a indicating multiple cycles of freeze-thaw activity and translocation of fine particles (red arrow); (c) banded fabric preserved within insect burrow (green arrow) and rounded vesicles (red arrow) indicating collapse of banded structure across the unit as shown in sample CC-5-4a; (d) well-developed vesicular structure (blue arrows) within LU3 (sample CC-5-3b) silt indicating rapid thawing; (e) vesicular structure as mamillated vesicles (purple arrows) within LU4a silt loam (sample CC-5-4a); (f) well-developed vesicular structure (orange arrows) within Feature 3 (sample CC-5-2). Li = lithic, Cr = cryosuction; B = bone; bb = burned bone; c = charcoal; sc = silt cap. All photomicrographs are in plane polarized light (ppl).*

We also identified key pedofeatures associated with frost action. This includes few silt coatings and common silt caps throughout deposits dating to the YD at Connley Cave 5. Specifically, silt coatings only occur within LU2 but in the lower (> 5 cm) part of the deposit (Figures 3(a); 4(a)). Silt caps on coarse clasts occur within LU3 (Figure 4(b)), LU4a (Figure 4(c)), and within Feature 3 on microdebitage (Figure 3(f)). In LU4b, some silt caps include fragments of charcoal, likely derived from overlying hearth features.

Figure 4 *Younger Dryas-induced pedofeatures observed at Connley Cave 5: (a) silt coatings around coarse clasts (yellow arrows) within LU2 indicating rotation (lower half CC-5-3a); (b) silt caps on coarse clasts (red arrow) indicating translocation of fine particles (silt) within LU3 (CC-5-3b); (c) silt caps on coarse clasts (green arrow) within LU4a; (d) linear pores underlying coarse clasts (blue arrow) within LU2 indicating re-orientation of* *coarse clasts (frost jacking) (CC-5-3a); (e) frost jacking (orange arrows) within LU3 as observed in sample CC-5-3b; Li = lithic as microdebitage; (f) pores around coarse clasts within LU4a (purple arrows) as observed in sample CC-5-3c. All photomicrographs are in ppl.*

Finally, repetitive freeze–thaw cycles appear to have sorted some coarse fragments through the process of frost jacking, as indicated by linear pores surrounding clasts in LU2 (Figure 4(d)) and LU3 (Figure 4(e)). Regarding the latter, Figure 4(e) illustrates an example of anthropogenic inputs in the form of microdebitage that have been moved (perhaps only a few millimeters) *in situ* via frost jacking. However, only mild displacement (in the form of a few micrometers) is expected within LU4a and LU4b (Figure 4(f)). We observed no evidence of frost shattering at the Connley Caves, likely a result of the nature of dense basalts found within bedrock lithology.

5. Discussion

In North America's Great Basin, research over the last decade have revealed a well-dated archaeological record associated with the YD. As we demonstrated here, recent excavationsat Connley Caves has provided a unique opportunity to evaluate site formation processes occurring during the YD, especially the effects of abrupt cooling. Specifically, the effects of abrupt cooling on deposits preserving buried archaeological assemblages contained within Connley Caves are not always apparent at the outcrop scale. To our knowledge, this study represents the first to identify cryogenic features associated with the YD at the microscopic scale in the Great Basin. These results have several important implications for archaeology at Connley Caves, and other sites across the Great Basin.

5.1. Younger Dryas formation processes at Connley Caves

Soil micromorphology allows archaeologists to test field-generated hypotheses about how archaeological sites are preserved, altered, and destroyed (i.e., formation processes) (Courty, Goldberg, and Macphail 1989). At Connley Caves, we identified four informal lithostratigraphic units that were radiocarbon dated to the YD (LU2 – LU4b). In the field, we observed no evidence for major cryoturbation, such as frost heave involutions or injection features. However, the results of this study shed light on two previously observed sedimentological features within LU2 which provide clues into identifying the frost action at the macroscopic scale. These include: (1) texture and consistency, which in the field were described as moderately cemented and moderately hard silt loam due to compaction via frost desiccation; (2) the degree of structural development, which began as platy and shifted to subangular blocky with depth; and (3) the presence of ice-induced silt lenses within the top of LU2 (Figure 5). Given that these features have not been identified as associated with frost-action in the Great Basin, previous research hypothesized that the formation of the cemented unit (LU2) may be due to the translocation of calcium-rich water down profile to the bottom of the cave (Jenkins, Holcomb, and McDonough 2017). The results of soil micromorphology allow us to reject that hypothesis and instead demonstrates that LU2 formed through a complex sequence of frost-action and cryogenesis, including (1) compaction from frozen ice, as indicated by platy structure in the upper 5 cm; (2) cementation due to frost-desiccation indicated by multiple cycles of overlapping banded microstructures; (3) frost creep induced lateral movement, indicated by the lenticular microstructure and silt coatings in the bottom part of LU2; and (4) soil development during a period of stability, as suggested by the

subangular blocky structure, indicating LU2 as a cryogenic buried soil. **Figure 5** (a) Profile view of Unit 19 from Cave 5. Note silt laminae within top of LU2 (red arrow), which may be wrongly interpreted as water-lain, but are instead a product of ice lensing during the Younger Dryas; (b) plan view of the surface of LU2, showing the undulating and moderately cemented nature of the deposit which was formed by a complex interaction between frost desiccation and frost creep; (c) cryogenic subangular to subrounded blocky soil structure within LU2.

These data have several implications for understanding the formation of deposits preserved within Connley Cave 5. First, the sedimentological characteristics that make up LU2, including its light color, cementation, structure, and sorting are not depositional, but were formed post-depositionally or cryogenically during the YD. Second, the lack of similar cryogenic features within the overlying unit LU3, coupled with the platy structure of the upper 5 cm of LU2 and abrupt clear lower boundary of LU3, suggests that the contact between LU2 and LU3 represents a buried surface. Radiocarbon dates from LU3 in Cave 5 range from ca. 10,420–10,650 ^{14}C yr BP. Although undated in Cave 5, radiocarbon dates from LU2 within Cave 4 range from ca. 10,770–11,100 ^{14}C yr BP, indicating a several hundred-year allostratigraphic gap between these two units marking a period of landscape stability and subsequent soil development (cryogenic). Following this period of stability, sedimentation outpaced pedogenesis throughout the rest of the YD. Finally, despite identifying microscopic features (silt caps on coarse clasts and vesicular structures) within LU4a, these features were not observable in the field-setting, further highlighting the importance of evaluating YD-aged deposits at the micro-scale.

5.2. Evaluating cryoturbation at Connley Caves

Perhaps of most interest to archaeologists working in the Great Basin is the role that frost action can have on the archaeological assemblages preserved within YD-aged deposits (i.e., cryoturbation). The micromorphology results presented here, while qualitative, offer a preliminary approach for evaluating cryoturbation at Connley Caves. Field data from motion experiments and micromorphological observations on cryosols by Van Vliet-Lanoë (1987; 1995) have provided a basis for generating hypotheses about cryoturbation or disturbances at the micro-scale (Figure 6). Specifically, the consideration of various microfabrics, microstructures, pedofeatures, and coarse clast deformations together provide researchers with a way to consider the degree of lateral and vertical movement of a soil fabric

or coarse clast (e.g., artifact) that could be expected in a general sense. **Figure**

6 Relationship between freeze-thaw process, resulting microfabric, microstructures, and pedofeatures, and their implications for disturbance related to observations made at Connley Cave 5 (adapted from Van Vliet-Lanoë, Fox, and Gubin 2004).

At Connley Cave 5, coarse clasts within LU2 reveal evidence for some degree of vertical sorting of coarse clasts (frost jacking), as well as lateral movement in the form of frost creep, though it appears to be stronger in the lower half of the deposit. For example, the upper 5-10 cm of LU2 exhibits a platy soil structure at the macro-scale, and a banded microstructure with silt caps, suggesting a normal degree frost creep of around 1–10 mm. Below 10 cm, however, LU2 expresses a more lenticular microstructure with silt coatings, indicating a stronger degree of frost creep and coarse clast rotation. This suggests an accelerated degree of frost creep or lateral movement for the lower part of LU2, likely owing to differences in water supply during thaw (Van Vliet-Lanoë 1998, 165). These data have implications for the movement and migration of biomolecules, especially for future sedaDNA studies, at Connley Caves and similarly-aged sites throughout the Great Basin. However, to date no artifacts have been found in the lower half of LU2.

Soil micromorphology of LU3, LU4a, and LU4b also demonstrated that these units were affected by frost action, but to a milder degree, as demonstrated by the presence of silt caps, cryosuction (pores below coarse clasts), and vesicular microstructures. These features are typical of rapid freeze–thaw and translocation of fine silts, and we can hypothesize that assemblages within these units experienced mild (< 1 to 1 mm) disturbances. Recent analysis of combustion features dated to the YD within LU4a and LU4b support this hypothesis given their original structures are preserved at the macroscopic scale, including in-tact dish shapes and rock lined features (McDonough et al. 2022). Future research can evaluate these hypotheses further by applying refit and spatial mapping analyses to artifact assemblages. Moreover, an increased soil micromorphology study is underway at Connley Cave 5 and will seek to further evaluate these findings.

5.3. Younger Dryas climate variability

While preliminary, these results provide some general hypotheses to be tested about YD paleoenvironmental conditions in the northern Great Basin. Traditional narratives about the YD typically characterize the chronozone as a period of cool-wet conditions (e.g., Goebel et al. 2011). Soil micromorphology suggests that Connley Caves experienced paleoenvironmental conditions typical of periglacial environments, as well as a potential "two-stage" model of climate variability. For example, although water supply is a major factor for understanding the generation of cryogenic features, the preliminary data here suggest that frost action was more pronounced deeper in the site, and therefore perhaps earlier within the YD. Banded fabrics are well-expressed within LU2, dating > 10,600 ^{14}C yr BP, but following 10,200 ^{14}C yr BP onwards they collapsed into vesicular structures indicative of rapid thawing. While these results are preliminary, they may provide evidence to support hypotheses for a more variable YD, including a shift from cool-mesic conditions during the early YD to cool-arid conditions by the end of the YD. This is a hypothesis that warrants further investigation through multiple analytical techniques (e.g., paleobotany, geochemistry), but, such conclusions are in line with and appear to support other geological studies suggesting a more variable “two-stage” YD, including those from alkenone-based sea surface temperature reconstructions (Barron et al. 2003), hydroclimate data (Pigati and Springer 2022), palynological and diatom records from lake cores (Anderson, Lozhkin, and Brubaker 2002; MacDonald et al. 2008; Mensing 2001), bulk sediments sampled from nearby Paisley Caves (Beck, Bryant, and Jenkins 2018), carbon isotopes ($\delta^{13}C$) from packrat middens (Cole and Arundel 2005), and oxygen isotopes ($\delta^{18}O$) from speleothems (Vacco et al. 2005). The claim that soil micromorphology at Connley Caves support a two-stage YD climate will be investigated further by increased soil micromorphology sampling and the application of complementary analytical techniques (e.g., geochemistry, mineralogy, and paleobotany).

Understanding the degree of climate variability during the YD is crucial for interpreting the archaeological record and human-environment dynamics during this time. A primary question at Connley Caves and in Great Basin research more broadly, is how people experienced and adapted to shifting paleoenvironmental conditions at the end of the Pleistocene. Analyses of hearth features in Connley Cave 5 (McDonough et al. 2022) and tool assemblages in Cave 4 (Rosencrance et al. 2022) show that people engaged in a wide range of activities including hunting, plant gathering, tool making, and sewing during various visits throughout the YD. These studies suggest that people were using Connley Caves differently and more frequently during the Younger Dryas relative to the Early Holocene (Rosencrance et al. 2022). Cryogenic features identified in this study contribute to the environmental data needed to understand how variability in site use may relate to changes in climate conditions. For example, how did changing temperatures and water availability affect vegetation communities and food sources? Is the prevalence of eyed bone needles in YD contexts at Connley Caves related to the construction of tight-fitted clothing to survive frigid winters (Osborn 2014)? Proxy data are especially crucial in the Fort Rock Basin, which is renowned for its early archaeological record (e.g., the oldest dated footwear in the world at Fort Rock Cave (Connolly et al. 2016)) but suffers from a paucity of local paleoenvironmental data (McDonough 2021).

5.4. Implications for Great Basin archaeology

The identification of cryogenic features generated during the YD at Connley Caves has implications for archaeological sites in the northern Great Basin, but also potentially elsewhere, including those in rockshelter, cave, and open-air settings. First, the identification of frost action at the micro-scale indicates the presence of periglacial environmental conditions and can be used as a chronological age. For example, due to the erosive nature of pluvial lake-levels at the end of the Pleistocene, caves and rockshelters in the northern Great Basin typically preserve sediments dating after the Late Glacial Maximum (< 21,000 cal yr BP) (Adams et al. 2008; Wriston and Smith 2017). Thus, the identification of frost action can therefore be used to directly demonstrate a YD age for sediments and soils found within similar settings in the northern Great Basin, and perhaps beyond.

These results also suggest that other sites in the Great Basin dating to the LP/EH with artifact assemblages preserved within YD-aged contexts could be affected by cryoturbation and should be evaluated with soil micromorphology. For example, archaeological sites that have encountered cemented deposits, such as the "compact sandy loam" at Bonneville Estates Rockshelter (Graf 2007) or "indurated organic sandy deposits" at Paisley Caves (Jenkins et al. 2012; Shillito et al. 2018), may signal the presence of frost action. Meanwhile, potential future work at sites within similar settings in the northern Great Basin, such as Cougar Mountain Cave, OR, as well as open-air sites, such as Weed Lake Ditch, OR (Smith et al. 2020; Wriston 2003) and Wishbone, NV (Duke et al. 2022), should also consider incorporating microscopic approaches such as soil micromorphology. Specific microscopic cryogenic features that can be identified and can alter spatial orientation of artifacts include frost creep-induced microstructures, such as rounded ped structures, silt coatings, and linear voids underlying coarse clasts indicative of frost jacking and cryosuction.

6. Conclusion

This study highlights the importance of microscopic approaches – such as soil micromorphology – for evaluating site formation processes and reconstructing paleoenvironments across the LP/EH transition. We identified microscopic cryogenic features observed within sediments and soils at Connley Caves including banded, rounded (granular), and vesicular microstructures, linear pores underlying (cryosuction) and surrounding (frost jacking) coarse clasts, silt caps (freeze–thaw cycling), and silt coatings (frost creep) from YD-aged deposits. These data have implications for archaeological assemblages preserved within the site, and while the degree of disturbance in archaeological-bearing units is minimal, future work will seek to further test issues of cryoturbation through refitting and spatial analyses of buried assemblages. The movement of sediments, even if only by a few mm, also has implications for the emerging applications of methods such as sedaNDA or biomarkers, which rely on linking microscopic biomolecules with ^{14}C dated material linked by context (Shillito et al. 2018). The identification of cryogenic features at the micro-scale equips researchers with the ability to identify the Younger Dryas in the northern Great Basin, providing another line of evidence for understanding LP/EH paleoenvironments. This research highlights the important role that soil micromorphology has for identifying and evaluating formation processes in the Great Basin especially during periods of abrupt climate variability, such as the Younger Dryas chronozone.

Disclosure statement

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