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Vesicular horizons are thin (usually <10 cm) surface or near-surface horizons characterized by the predominance of vesicular porosity. They are widespread in arid and semiarid lands, occurring on every continent and covering 156,000 km^2 of the western United States. Vesicular horizons have critical implications for management due to their role in controlling surface hydrology and dust mobilization. This study evaluates the distribution and variation in expression of vesicular horizons across the western United States using the soil databases available from the USDA. A vesicular horizon index (VHI) that incorporates vesicular horizon thickness and the size and quantity of vesicular pores was developed using soil descriptions from a published chronosequence study. The VHI was applied to descriptions from the soil survey databases to evaluate vesicular horizon expression across the western United States. Vesicular horizons were better expressed (higher VHI) in the Central and Northern Basin and Range compared to the Mojave and Sonoran Basin and Range. This may be due to differences in temperature regime or to larger areas of playas in the Central and Northern Basin and Range that serve as sources of dust that forms the parent material for vesicular horizons. The median VHI was highest in the Aridisols and Mollisols compared to other soil orders. No significant relationship was found between VHI and soil textures. Vesicular horizons are widely distributed in western United States and occur across a wide range of soil types and soil-forming environments.

Abbreviations: CBR, Central Basin and Range; cry, cryic; DP, drying period for vesicular horizon after a precipitation event; frig, frigid; fsl, fine sandy loam; hyp, hyperthermic; MOJ, Mojave Basin and Range; NASIS, National Soil Information System; NBR, Northern Basin and Range; OSD, official series description; mes, mesic; Q, vesicular pore quantity class; S, vesicular pore size class; sil, silt loam; SDI, soil development index; sl, sandy loam; SON, Sonoran Basin and Range; SSURGO, Soil Survey Geographic dataset; STATSGO, State Soil Geographic dataset; therm, thermic; vfsl, very fine sandy loam; VHI, vesicular horizon index; X_{ve}, vesicular pore term; ΔT, increase in temperature during drying of the vesicular horizon.

The vesicular horizon is a surface or near-surface horizon characterized by the predominance of bubble-like vesicular pores (Fig. 1). They are a common feature of soils in arid and semiarid lands and play an important role in controlling the surface hydrology (Young et al., 2004) and dust emissions (Goossens and Buck, 2009) in the landscapes where they occur. Vesicular horizons are common in extremely arid, arid, and semiarid lands around the world (Fig. 2), and have been reported in salt flats in a subhumid setting as well (Fig. 2, Ref. 3). The expression of vesicular horizons is heterogeneous on multiple scales. For example, in an alluvial fan or bajada landscape (Peterson, 1981), the vesicular horizons vary with the age of the geomorphic surface on which they occur (McDonald, 1994), while within a single geomorphic surface vesicular horizons are well expressed in the shrub interspace, with limited or no occurrence in the shrub islands (Eckert et al., 1978; Shafer et al., 2007). Vesicular horizons are associated with certain types of surface cover, including physical and biological surface crusts, as well as desert pavement (Eckert et al., 1978).

It has consistently been observed that parts of the landscape with vesicular horizons have much lower infiltration rates compared to those without vesicular

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Fig. 1. Photograph of vesicular horizon with platy structure (Dixie Valley, NV).

horizons (Table 1). As a result, runnoff and ponding are more common on parts of the landscape with vesicular horizons (Eckert et al., 1978; Brown and Dunkerley, 1996). The low infiltration rates can be attributed primarily to the development of the vesicular horizon, rather than any underlying horizon, since infiltration rates increase dramatically when the vesicular horizon is removed (Young et al., 2004). Negative correlations have been observed between the abundance of vesicular pores in the surface horizon and infiltration rates (Blackburn, 1975; Valentin, 1994; Lebedeva et al., 2009), further suggesting that the vesicular horizon is a critical regulator of infiltration. Soil development in deserts, including vesicular horizon formation, tends to reduce the plant water supply, leading to lower shrub densities (McAuliffe, 1994) and more drought-adapted species (Hamerlynck et al., 2002) on older surfaces. Desert landscapes are characterized by clusters of plants in "islands of fertility" separated by barren shrub interspaces (Schlesinger et al., 1990). This pattern is reinforced by stronger expression of vesicular horizons, and resulting in runoff of water from shrub interspace and concentration of runon in the "islands of fertility," where infiltration rates are higher (Shafer et al., 2007). Vesicular horizons are better expressed under increasingly arid conditions, which may create a positive feedback that promotes desertification in semiarid lands by reinforcing hydrologic and ecological patterns characteristic of desert shrublands (Lebedeva et al., 2009).

Vesicular horizons are often best expressed on geomorphic surfaces that trap dust. This includes surfaces that are mantled by desert pavement, a monolayer of interlocking clasts that occurs at the surface of many desert soils (Wood et al., 2005). The primary mechanism of desert pavement formation is through vertical inflation by eolian materials trapped beneath the surface clasts (McFadden et al., 1987; Wells et al., 1995). This process causes a smoothing of the original surface topography and the accumulation of an eolian mantle that favors the formation of vesicular horizons and other pedogenic features. Relatively weak expression of vesicular horizons has been observed on landforms with smooth microtopography (e.g., sandy beach ridges) compared to those with initially rough microtopography that favors dust entrapment and desert pavement formation (e.g., gravelly piedmont and lava flows) (McFadden et al., 1992). The eolian origin of vesicular horizons has been supported in settings where the suite of minerals contributed by dust is distinct from the underlying parent material (Wells et al., 1985; Ugolini et al., 2008). The vesicular horizon is often formed predominantly in eolian parent materials, even when the underlying soil horizons are formed in another parent material, such as alluvium (McDonald, 1994) or glacial till (Rossi, 2009).

As a consequence of their eolian origins, soils with vesicular horizons are prone to high dust emission when they are disturbed by human activities, such as off-road driving (Goossens and Buck, 2009). Dust released from soil disturbance can have adverse effects on human health (Smith and Lee, 2003) and far-reaching ecological impacts. Desert dust deposited on alpine snow packs reduces their albedo, thereby increasing their melting rate and altering the hydrology of major river systems (Painter et al., 2010).

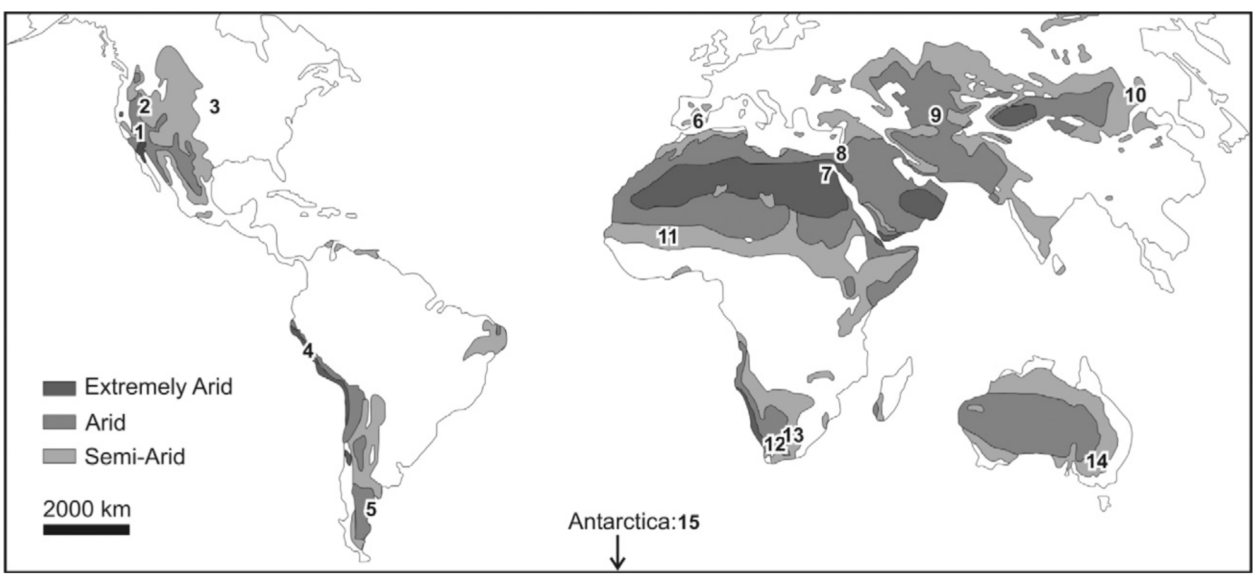

Fig. 2. Examples of studies recognizing vesicular horizons around the world, in relation to the global distribution of extremely arid, arid, and semiarid lands (USGS, 1997). References: (1) McDonald, 1994, (2) Blackburn, 1975, (3) Joeckel and Clement, 1999, (4) Noller, 1993, (5) Bouza et al., 1993, (6) Cantón et al., 2003; (7) Adelsberer and Smith, 2009; (8) Amit and Gerson, 1986; (9) Paletskaya et al., 1958; (10) Lebedeva et al., 2009; (11) Valentin, 1994; (12) Ellis, 1990; (13) Henning and Kellner, 1994; (14) Brown and Dunkerley, 1996; (15) Bockheim, 2010.

Vesicular horizons occur at or near the soil surface and are commonly thin (<10 cm) (Anderson et al., 2002). The morphological feature that distinguishes vesicular horizons from other surface horizons is the predominance of isolated, nearly spherical vesicular pores. Columnar or prismatic structure that parts to platy structure is a common, but not universal, feature of vesicular horizons. The pedogenic processes that form vesicular horizons include: (i) the additions of eolian material to the soil surface, (ii) the development of a surface seal in the form of an embedded gravel layer or a physical or biological crust, and (iii) wetting and drying cycles that cause the growth of vesicular pores and their collapse to form platy structure (Fig. 3). The role of wetting and drying cycles in the formation of vesicular pores has been observed in laboratory studies in which vesicular pores are regenerated through the wetting and drying of crushed soils (Springer, 1958; Miller, 1971; Evenari et al., 1974; Figueira and Stoops, 1983). Wetting and drying cycles also cause polygonal cracking and the formation of prismatic or columnar structure in the vesicular horizons. The vesicular pores are believed to be formed by air that is trapped as bubbles during the wetting of an initially dry soil. The presence of a gravel layer or a physical or biological crust prevents the trapped air from escaping at the soil surface (Evenari et al., 1974). Vesicular pores are more common under embedded surface rock fragments compared to nonembedded rock fragments, due to the more effective surface sealing (Valentin, 1994). The formation of vesicular pores has been associated with silt-rich soil materials (Miller, 1971). The addition of eolian materials to the surface of desert soils helps to create conditions for vesicular pore formation by enriching the soil surface in silt-sized particles. The process of eolian additions may continue even in well-developed vesicular horizons. This material is carried into the vesicular horizon with infiltrating water, resulting in a progressive thickening of the vesicular horizon and the formation of ped surface features that may help to stabilize the vesicular pores and platy peds (e.g., argillans and calcite coating) (Sullivan and Koppi, 1991; Anderson et al., 2002; Lebedeva et al., 2009).

Table 1. Summary of studies finding lower infiltration rates in soils with vesicular horizons compared to soils without vesicular horizons in the same landscape. Regions are designated as SON = Sonoran Basin and Range, MOJ = Mojave Basin and Range, CBR = Central Basin and Range.

Region	Dominant vegetation	Interspace surface cover	Infiltration rate, cm h^{-1}		Reference
			Vesicular	Nonvesicular	
SON	*Larrea divaricata*, *Ambrosia dumosa*	Desert pavement	0.8	6.0–9.6	Musick, 1975
MOJ	*Larrea tridentata*, *Ambrosia dumosa*, *Yucca* spp.	Desert pavement	0.3–0.8	6.8–15	Young et al., 2004
MOJ	*Larrea tridentata*	Desert pavement	1.3–4.6	8.9	Miller et al., 2009
MOJ/CBR	*Coleogyne ramosissima*, *Ephedra nevadensis*, *Atriplex canescens*	Desert pavement	1.2–4.5	5.5–17	Shafer et al., 2007
MOJ/CBR	*Larrea tridentata*, *Coleogyne ramosissima*	Desert pavement	0.4–1.4	3.1–3.2	Eckert et al., 1979
CBR	*Artemisia* spp.	Bare ground	1.7–3.2	5.8–7.2	Blackburn, 1975

The process of vesicular pore formation can occur rapidly. In the lab, vesicular pores are observed to form in crushed and sieved soil material, collected from vesicular horizons, over 4 to 25 wetting and drying cycles (Miller, 1971; Figueira and Stoops, 1983). In the field, vesicular pores were observed to reform in disturbed soils after only 4 mo (Yonovitz and Drohan, 2009). Thin vesicular horizons (<1 cm) have been observed on very young (<100 yr) geomorphic surfaces (Gile and Hawley, 1968) and surfaces subject to active sediment transport (Peterson, 1980). Chronosequence studies in the Mojave Desert have suggested that vesicular horizons are the first indicators of soil development (McFadden et al., 1986; McFadden, 1988). The rapid formation of vesicular pores indicates that they are a dynamic soil property. However, the eolian surface horizon, containing material that is conducive to vesicular pore formation, may be considered a stable feature, unless physical disturbance (Goossens and Buck, 2009) or a change in hydrologic conditions (Wells et al., 1985) causes erosion of the surface material.

A wealth of pedon descriptions, using a consistent terminology for describing key features of the vesicular horizon (e.g., the size and quantity of vesicular pores) is available through the USDA databases of Official Soils Descriptions (OSDs) (Soil Survey Staff, 2009a) and National Soil Survey Characterization Data (Soil Survey Staff, 2009b). We used these databases to study the distribution and properties of vesicular horizons across the western United States. Our objectives were to (i) use soil database information to characterize the distribution of vesicular horizons and their range of physical and chemical properties, (ii) to

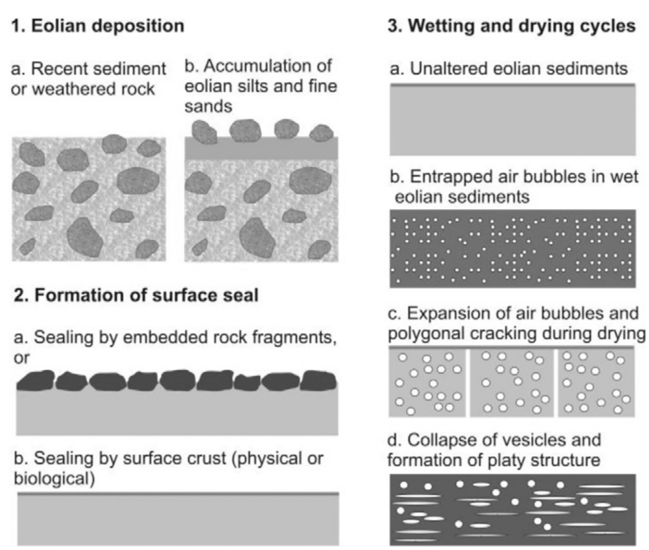

Fig. 3. Summary of processes central to vesicular horizon formation.

develop a field index for quantifying vesicular horizon expression, and (iii) to apply the developed field index to the soil database information, to evaluate trends in vesicular horizon expression across different ecoregions (i.e., hot and cold deserts) and among soils with varying properties (i.e., soil temperature regimes, soil orders, and textures). This broad evaluation of vesicular horizon distribution and variability in expression is intended to reveal the extent of this feature, as well as to examine patterns that may help us unravel the mechanisms involved in vesicular horizon formation. The vesicular horizon's near-surface position, its control of surface hydrology (Young et al., 2004), and its sensitivity to dust mobilization (Goossens and Buck, 2009), as well as the dynamic nature of vesicular porosity (Yonovitz and Drohan, 2009) make it an important feature to be recognized in land-use planning and studies of ecological change in arid and semiarid lands.

MATERIALS AND METHODS

Analysis of Soil Databases

Soil series with vesicular horizons were found by searching all OSDs (Soil Survey Staff, 2009a) in the 11 western states for the term "vesicular" and checking each description for vesicular pores in a horizon that starts within the upper 10 cm of the soil surface. Only those descriptions in which the vesicular pores had a higher quantity class than all other pore types were included in the dataset. These criteria were used to limit the dataset to those horizons that restrict infiltration rates because they are close to the surface and are dominated by noninterconnected porosity. The area of soil series with vesicular horizons mapped in the Soil Survey Geographic (SSURGO) dataset was determined using the Soil Extent Mapping Tool (Soil Survey Staff, 2007). This evaluation represents a minimum estimate of the area of vesicular horizons, since areas mapped after 2007, including many soil survey areas in arid and semiarid regions, are not yet entered into the Soil Extent Mapping Tool. The distribution of soils with vesicular horizons was also evaluated using the State Soil Geographic data set (STATSGO) (USDA-NRCS, 2006), by selecting all map units in which one or more major components is a soil series with a vesicular horizon in the OSD. This data set lacks the resolution and accuracy of the SSURGO data, but offers a complete, broad-scale depiction of vesicular horizon occurrence in the western United States.

The names of the soil series with vesicular horizons were used to query the National Soil Survey Characterization Data (Soil Survey Staff, 2009b) for lab data and National Soil Information System (NASIS) pedon descriptions of soils with vesicular horizons. Using both OSDs and NASIS pedon descriptions creates potential for duplication of data points, because some OSDs are also in NASIS. To avoid this problem, all OSDs that had the same location description as a NASIS pedon descriptions were removed from our dataset. The location of each pedon description with a vesicular horizon (type location for the OSDs) was plotted using ArcMap 9.3 (Esri, 2008). Locations recorded using the Public Land Survey System were converted to an approximate latitude and longitude using Graphical Locator (Gustafson, 2003).

Development and Application of the Vesicular Horizon Index

The methods for developing a field index for the vesicular horizon were based on those used by Harden (1982) to evaluate the soil development index (SDI). The index was evaluated using pedon descriptions from a published chronosequence study in the Mojave Desert (McDonald, 1994), according to the most recent evaluations of surface age at the site (McDonald, 2008). This chronosequence study, located on a series of alluvial fan deposits of the Providence Mountains in California, was selected because it includes a high level of replication (5–15 pedon descriptions per surface age) and a wide range of surface ages (750–135,000 yr).

The VHI was then applied to our dataset of pedon descriptions with vesicular horizons, derived from the USDA databases, and used to analyze variability in the vesicular horizon expression across the western United States. The pedon description locations were overlaid with Level III Ecoregions (USEPA, 2006a) to group the points in a way that reflects spatial variability in climate and biotic factors. The VHI was compared among soils grouped by ecoregions of the Basin and Range Province, including the Sonoran Basin and Range (SON), Mojave Basin and Range (MOJ), Central Basin and Range (CBR), and Northern Basin and Range (NBR) ecoregions. The Basin and Range Province was selected for analysis because vesicular horizons are frequently described in this region (see Fig. 4a) and the ecoregions represent a gradient of climatic and biotic influences. The SON and MOJ ecoregions are considered warm deserts, while the CBR and NBR are considered cold deserts (USEPA, 2006b). The VHI was also used to compare vesicular horizon expression among different soil orders, soil temperature regimes, and vesicular horizon textures.

Due to the non-normal distribution of VHI, all statistical tests were performed using nonparametric analyses, including the Kruskal–Wallis test (Sheskin, 2007) for comparison among all groups and the Mann–Whitney test (Sheskin, 2007) and Bonferonni correction (Abdi, 2007) for comparisons between specific groups. All nonparametric analyses were performed using MINITAB 15 (Minitab, 2007) and the Bonferonni correction was calculated by hand.

Analysis of Weather Records

To consider the relationship of VHI to modern climate conditions, weather records were analyzed at 20 Remote Automated Weather Stations (RAWS) (Western Regional Climate Center, 2011), including five stations in each of the ecoregions discussed above (SON, MOJ, CBR, and NBR). The stations were selected based on proximity to database pedon descriptions with vesicular horizons (Fig. 4a). Two climatic variables were extracted: (i) the average number of precipitation events per year and (ii) the average increase in temperature during the drying period following a precipitation event (ΔT). These variables are considered the most significant in terms of understanding the relation of climate to vesicular pore formation. Vesicular pores only form and expand when the soil is wet (Springer, 1958; Miller, 1971; Figueira and Stoops, 1983), presumably because vesicular horizons have a weak structural consistence when they are wet (Bouza et al., 1993).

The amount of time required for the vesicular horizon to dry following a precipitation event, hereafter called the drying period, is a critical assumption that influences the analysis of both of the extracted variables. The drying period was used to define the split between successive pore-forming precipitation events. This was because the soil will only trap air and form vesicular pores if it has dried first, thus introducing

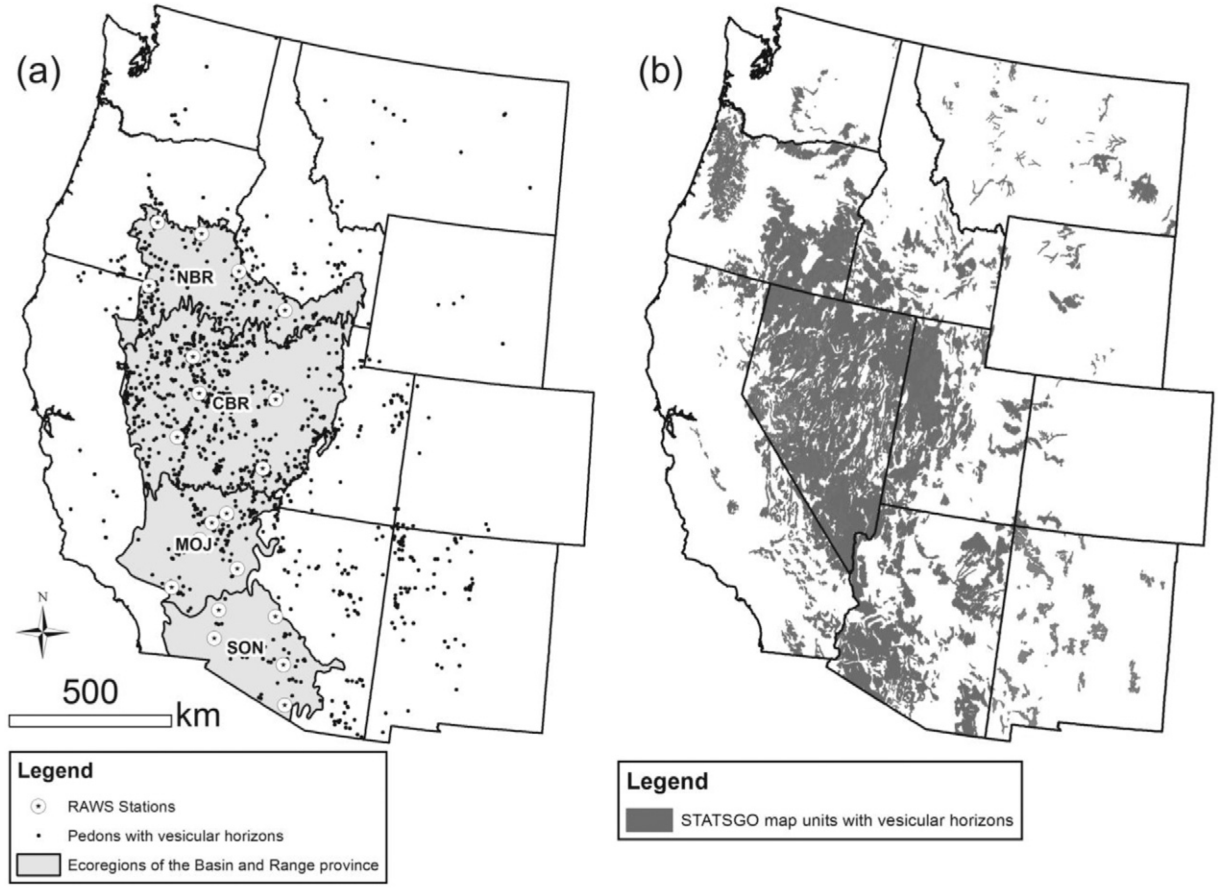

Fig. 4. Spatial distribution of soils with vesicular horizons indicated by: (a) Soil descriptions with vesicular horizons, including Official Series Descriptions (OSDs) and National Soils Information System (NASIS) pedon descriptions and the location of Remote Automated Weather Stations (RAWS) used in climate analysis and (b) State Soil Geographic data set (STATSGO) map units in which one or more major components are soil series with a vesicular horizon in the OSD. Shaded areas in (a) indicate the ecoregions of the Basin and Range Province, SON = Sonoran Basin and Range, MOJ = Mojave Basin and Range, CBR = Central Basin and Range, NBR = Northern Basin and Range.

more air to be trapped. The ΔT was defined as the difference between the maximum temperature during the drying period and the temperature at the time of initial precipitation. Air temperatures were used for this analysis, rather than soil temperatures, because these data were readily available and because the vesicular horizons typically occur at the soil surface, where temperature fluctuations are most directly influenced by aboveground weather conditions.

The actual drying period depends on current weather conditions (e.g., air temperature, relative humidity), the water retention characteristics of the vesicular horizons, the relationship between water content and consistence of the vesicular horizon, and drainage conditions of the soil. Our analysis assumed a drying period of 1 d during the summer (June–August), 5 d during the winter (December–February), and 3 d at other times of the year. These assumptions were based on casual observations of vesicular horizon behavior in the field. Thorough verification of these assumptions was beyond the scope of this study, but we did consider the sensitivity of our analysis to the assumption of drying period (Table 2). Assumption of a longer drying period results in calculation of fewer precipitation events per year and a greater ΔT. Using a longer drying period resulted in fewer precipitation events because the drying period was used to define the separation of successive precipitation events, therefore using a longer drying period causes more precipitation to be lumped into a single event. The impact of this assumption was similar at climate stations located in each of the ecoregions and therefore is not presumed to introduce any bias to our comparison between ecoregions. Precipitation events of <5 mm were not included in the analysis, as small events are unlikely to be effective at trapping air and forming vesicular pores. Our analysis included between 5 and 10 yr of weather records at each RAWS site. The annual number of precipitation events and ΔT were compared between the ecoregions according to ANOVA and multiple comparisons using Tukey's test (Sheskin, 2007). Statistical analysis was performed using MINITAB 15 (Minitab, 2007).

RESULTS AND DISCUSSION

Distribution and Range of Properties

The analysis of soil databases produced 1092 OSDs and 295 NASIS pedon descriptions with vesicular horizons. Soils with vesicular horizons occur throughout the western United States, but have been described most frequently in the Basin and Range Province, particularly in the NBR and CBR (Fig. 4a). This distribution may be biased by differences in the intensity of sampling across different soil survey areas and the scarcity of points in areas where soil surveys have not been completed (e.g., the Mojave Desert region of California). The distribution of soil series with vesicular horizons derived from the STATSGO dataset (Fig. 4b) may provide a better depiction of the overall distribution of

Table 2. Influence of assumed drying period on calculation of ΔT and the frequency of precipitation events.

RAWS Site (Ecoregion)†	ΔT‡			Annual precipitation events		
	DP = 1 d§	DP = 3 d	DP = 5 d	DP = 1 d	DP = 3 d	DP = 5 d
Haley Hills, AZ (SON)	7.5 ± 0.6¶	11.2 ± 0.6	12.8 ± 0.7	8.1 ± 1.2	7.5 ± 1.0	7.0 ± 1.0
Horse Thief Springs, CA (MOJ)	5.9 ± 0.4	9.7 ± 0.5	11.6 ± 0.5	10 ± 0.9	8.3 ± 0.6	7.4 ± 0.6
Austin, NV (CBR)	7.4 ± 0.5	11.3 ± 0.6	13.5 ± 0.7	10.8 ± 0.9	9.8 ± 0.8	7.9 ± 0.5
Triangle, ID (NBR)	6.1 ± 0.4	9.2 ± 0.5	11.3 ± 0.6	13.5 ± 1.2	11.1 ± 0.9	10 ± 0.7

† Ecoregions: SON = Sonoran Basin and Range, MOJ = Mojave Basin and Range, CBR = Central Basin and Range, NBR = Northern Basin and Range.

‡ ΔT = Increase in air temperature during vesicular horizon drying after a precipitation event.

§ DP = Drying period used to define the time required for vesicular horizon drying after a precipitation event.

¶ Mean ± 1 SE.

vesicular horizons. These data also show that vesicular horizons are extensive throughout the western United States, but are especially common in the Basin and Range Province. The total area of soil series with vesicular horizons mapped in SSURGO is 156,000 km^2 (as of 2007). Based on SSURGO, the vesicular horizons cover about 5% of the western United States and 21% of the Basin and Range Province.

The distribution of vesicular horizons in the western United States (Fig. 4), as well as the worldwide distribution of research sites where vesicular horizons have been described (Fig. 2), show that they mainly occur in arid and semiarid regions. Vesicular porosity is also better expressed under the more arid conditions across a climatic gradient in Mongolia (Lebedeva et al., 2009). The soils with vesicular horizons in our dataset derived from the USDA databases are mostly soils with aridic moisture regimes (72%). The association of vesicular horizons with arid ecoregions and soils with aridic moisture regimes can be attributed to a few factors: (i) high rates of dust deposition which create a surface layer that is conducive to vesicular pore formation (McFadden, 1988; McFadden et al., 1998), (ii) periodic drying and rewetting of the soil surface, which drives vesicular pore formation (Springer, 1958; Miller, 1971; Figueira and Stoops, 1983), and (iii) low vegetative cover, which allows surface crusting and air entrapment in the soil (Evenari et al., 1974).

The vesicular horizons in the soil databases occurred in a range of soil orders and were present across all temperature regimes. The soils included in the data set are mostly Aridisols (65%), but also include Mollisols (14%), Entisols (13%), Alfisols (5%), Inceptisols (3%), and a few Andisols and Vertisols (<1% each). The common occurrence of vesicular horizons in Aridisols reflects the association of vesicular horizons with arid environments. The temperature regimes of the soils with vesicular horizons were hyperthermic (4%), thermic (13%), mesic (64%), frigid (18%), and cryic (1%). Mesic and frigid temperature regimes were most common because many of the pedons with vesicular horizons were described in the cold deserts (i.e., CBR and NBR ecoregions) (Fig. 4a).

The most common field-determined texture of the vesicular horizons was loam (35%), followed by sandy loam (18%), silt loam (15%), fine sandy loam (13%), very fine sandy loam (6%), clay loam (4%), silty clay loam (3%), loamy sand (1%), coarse sandy loam (1%), and loamy fine sand (1%). Other textures (sand, silty clay, loamy coarse sand, clay, and coarse sand) each occurred in <1% of the vesicular horizons. Peterson (1980) observed a similar distribution of textures in the vesicular horizons of the Panamint Valley, California, which ranged from loamy sand to clay loam, but were most commonly sandy loam, loam, and silt loam. Laboratory-determined textures, available for 279 of the vesicular horizons, show a similar range of textures, but with stronger concentration of textures in the high-silt corner of the textural triangle (Fig. 5).

The geomorphic settings described in the NASIS pedon descriptions, grouped based on the classification of landforms by Peterson (1981), indicate that vesicular horizons are most common on piedmont landforms (alluvial fans, bajadas, fan remnants, fan skirts, fan terraces, and pediments) (72%), but also occur in mountains (mountainslopes, hillslopes, and structural benches) (13%) and basin floors (alluvial flats, alluvial plains, barrier flats, beach plains, lake terraces, playas, and sand sheets) (16%). Slopes reported in the NASIS pedon descriptions indicate that soils with vesicular horizons are generally on low slope gradients, with a median of 2% slope and an interquartile range from 1 to 5%, but can occur on slopes up to 45%. These findings are consistent with soil morphological descriptions made across an arid landscape in the Mojave Desert, in which vesicular horizons were observed to occur on landforms of the piedmont, mountains, and basin floor, but within the mountains, were more common on gently sloping landforms (e.g., mountainflat) compared to steep landforms (e.g., mountainflank) (Hirmas and Graham, 2011). Along a single hillslope in Australia, vesicular horizons were most common on low slope gradients as well (Brown and Dunkerley, 1996).

Vesicular horizons in the western United States occur across several ecoregions, which represent different climatic and biological influences, and are formed in various geomorphic settings, which represent differences in surface age, parent material, and relief. Thus, it is not surprising that the chemical properties of the vesicular horizon, including organic C, $CaCO_3$, pH, electrical conductivity, and exchangeable sodium percentage (ESP), vary widely (Table 3). Although some studies have suggested that low organic C (Wood et al., 1978), high $CaCO_3$ (Evenari et al., 1974), and high exchangeable Na percentage (Bouza et al., 1993) promote vesicular pore formation, none of these can be considered an essential prerequisite for vesicular horizon development. Of the soils analyzed, 68%

contained measureable $CaCO_3$ and only 11% were sodic soils (ESP > 15; U.S. Regional Salinity Laboratory, 1954).

Vesicular Horizon Index

The vesicular horizon index (VHI) was developed as a way to quantify vesicular horizon expression based on standard information recorded in field descriptions. Vesicular horizon expression is defined here according to the abundance of vesicular pores (more pores = better expression), the size of vesicular pores (larger pores = better expression), and the horizon thickness (thicker horizon = better expression). Previous studies have used similar rating systems for the purpose of comparing vesicular horizon expression within their study areas, based on the grade of platy and prismatic structure and the quantity class of vesicular pores (Blackburn, 1975; McDonald, 1994). Neither of these rating systems was suitable for application to the soil databases because they are not inclusive of all combinations of structure and porosity.

To develop an index that is inclusive of all possible ranges and combinations of properties that occur in vesicular horizons, the VHI was modeled after the soil development index (SDI) (Harden, 1982). In the SDI, the thickness of the soil horizons is multiplied by terms that quantify individual soil properties. The SDI does not include a term for vesicular porosity, therefore the first step in developing the VHI was to determine a suitable method for assigning a numerical value based on the description of vesicular pores. The standard method for describing vesicular pores includes the assignment of both a quantity class (Q) and size class (S) (Soil Survey Division Staff, 1993; Schoeneberger et al., 2002). Point values were assigned to Q (few = 10, common = 20, many = 30) and S (very fine = 10, fine = 20, medium = 30, coarse = 40, very coarse = 50) using intervals of 10 to be consistent with points assignments used in the SDI (Harden, 1982). Several possible combinations of Q and S were compared by calculating each of the candidate terms for soil descriptions from a chronosequence study in the Mojave Desert (McDonald, 1994) (Fig. 6). Two of the terms fit equally well to the chronosequence data ($r^2 = 0.89$, $p = 0.005$): (i) the term calculated by summing Q + S for all size classes included in the description and (Fig. 6b) and (ii) the term calculated by summing the product of Q × S for all size classes included in the description (Fig. 6d). The term calculated by summing Q + S for all size classes included in the description (Fig. 6b) was selected for use in the VHI because summation of soil property descriptors is more consistent with the calculations applied in the SDI (Harden, 1982). Following the notation used by Harden (1982), the vesicular pore term is denoted as X_{ve}. As in the SDI, X_{ve} is then set to a scale from 0 to 1 (X_{ven}) by dividing by the highest value of the term. The highest value for X_{ve} encountered in the soil databases was 220, this would represent a vesicular horizon with many very fine, many fine, many medium, and many coarse vesicular pores. Very coarse vesicular pores are rarely described and therefore not included in the calculation of the maximum X_{ve}. Finally, VHI is calculated by multiplying vesicular horizon thickness by X_{ven}. If more than one vesicular horizon is present in the soil profile, the VHI is calculated for each horizon and then summed. An outline and example of VHI calculation is provided in Fig. 7.

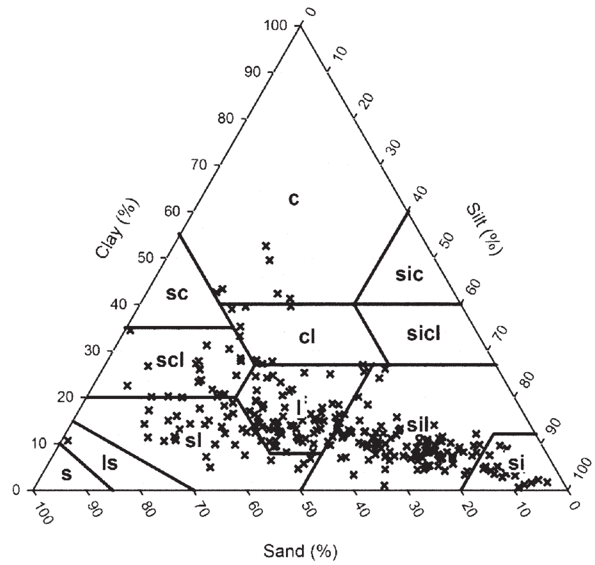

Fig. 5. Laboratory-determined textures of vesicular horizons plotted on the soil textural triangle.

The resulting index shows a strong relationship with the log of surface age ($r^2 = 0.94$) for the surfaces under 100,000 yr old (Fig. 8). These data demonstrate that although vesicular pores may be subject to collapse and reformation on a short time-scale (Fig. 3; Yonovitz and Drohan, 2009) there are also long term trends in vesicular horizon expression. This may be related to the addition of eolian materials to the vesicular horizon. Eolian additions cause the vesicular horizon to grow thicker. With age, the vesicular pores may also become stabilized by calcitans and argillans, which are formed by the transport of eolian-derived $CaCO_3$ and clay into the vesicular horizon with infiltrating water (Anderson et al., 2002). The decrease in VHI at the oldest site in the chronosequence (Fig. 8) can be attributed to dissection and erosion of this surface (Meadows et al., 2008). Although the VHI (which includes horizon thickness) decreases on the oldest surface, the X_{ve} increases (Fig. 6b). This suggests that X_{ve} alone may be a better indicator of surface age on dissected surfaces where the vesicular horizon has been partially eroded. However, this would only be true in cases where erosion has been rel-

Table 3. Chemical properties of vesicular horizons based on lab data for National Soils Information System pedon descriptions with vesicular horizons.

Property	Median	Interquartile range	Total range	N
Organic C, %	0.7	0.4–1.2	0–5.3	269
Electrical conductivity, dS m^{-1}	1.2	0.8–2.3	0.1–218	187
Exchangeable Na, %	2	1–6	0–96	256
pH	8.0	7.3–8.4	5–10.7	263
$CaCO_3$, %	4	0–12	0–49	205

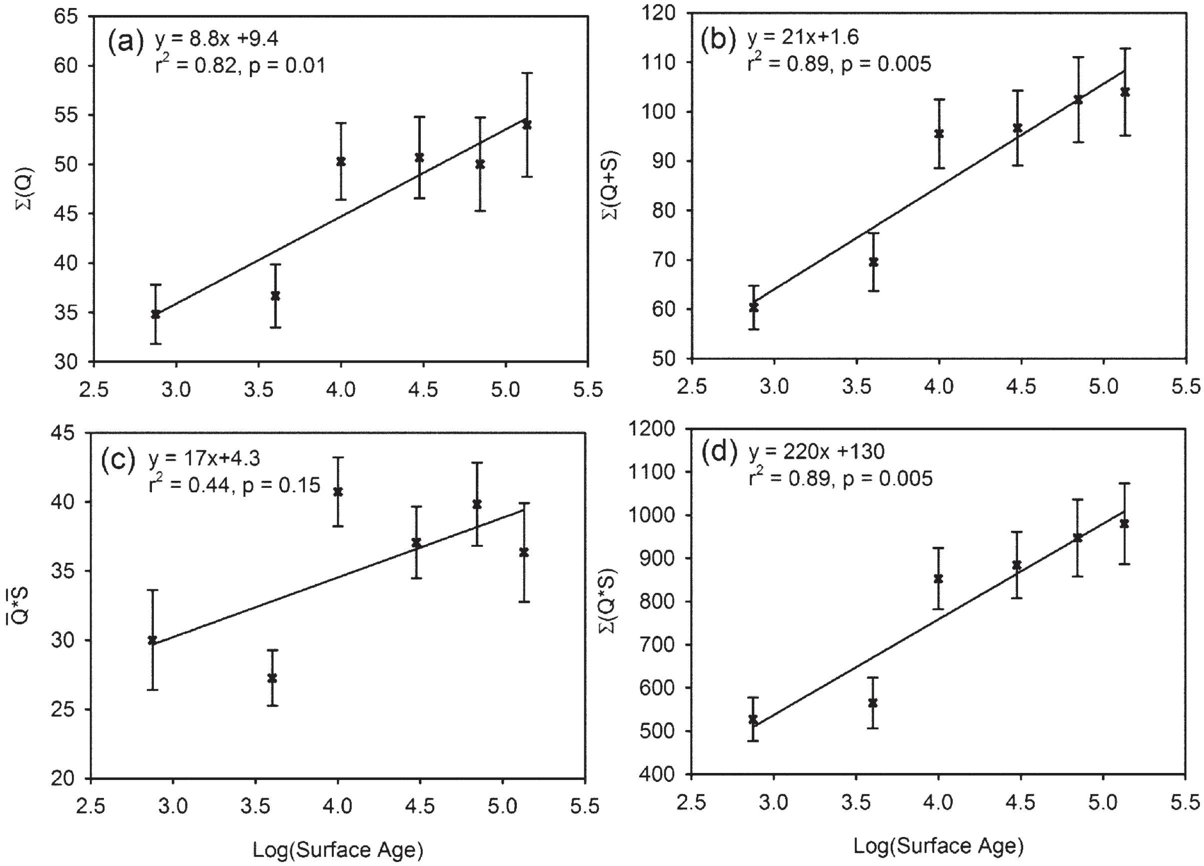

Fig. 6. Comparison of terms for the quantification of vesicular pore descriptions, applied to soils of increasing age on a chronosequence of alluvial fans in the Mojave Desert (McDonald, 1994): (a) ΣQ, (b) Σ(Q+S), (c) $\overline{Q}\times\overline{S}$, (d) Σ(Q×S), where Q = quantity class (few = 10, common = 20, many = 30) and S = size class (very fine = 10, fine = 20, medium = 30, coarse = 40, very coarse = 50). Error bars indicate one standard error.

atively minor. Severe erosion of well-developed desert soils has been described in chronosequence studies and attributed to a pedogenic threshold, in which reduced permeability due to soil development leads to runoff, dissection, and degradation of the surface (Wells et al., 1985). Under these circumstances the entire vesicular horizon would be removed and neither X_{ve} nor VHI would be reflective of the soil age.

The VHI is developed here for analyzing trends in vesicular horizon expression using soil databases, but it may be otherwise useful. The heterogeneity of vesicular horizons across desert landscapes could be used as an indicator of complex hydrologic patterns. Previous work has shown the infiltration rate of soils with vesicular horizons is negatively correlated with the quantity of vesicular pores described in the field (Blackburn, 1975; Valentin, 1994), as well as with the total porosity calculated from bulk density (Lebedeva et al., 2009). This suggests that VHI should also be negatively correlated with infiltration rate, although VHI is slightly different from the vesicular horizon rating systems used in the correlations described above, because it includes horizon thickness as well as vesicular porosity. Analysis of chronosequence data in arid and semiarid environments may also be aided by use of either the VHI or by including the X_{ve} term in the calculation of the SDI. Harden (1982) suggested that other terms could be added as the SDI is applied to chronosequences in various environmental settings, undergoing different pedogenic processes.

Vesicular Horizon Index and Ecoregions of the Basin and Range Province

A broad-scale trend across the Basin and Range Province is revealed when soil descriptions are grouped by Level III Ecoregions (USEPA, 2006a) (Fig. 9). The VHI is higher in the cold deserts (i.e., NBR and CBR) compared to the warm deserts (i.e., MOJ and SON). Possible regulators of vesicular horizon expression at this broad scale include paleoclimatic events, modern climatic conditions, and biotic factors.

The drying of pluvial lakes during interpluvial climatic periods exposed fine-grained sediments to wind erosion, producing vast areas that acted as dust sources. Episodic dust deposition from these events is an important driver of soil formation processes in both the warm (McFadden et al., 1986; McFadden, 1988) and cold deserts (Chadwick and Davis, 1990). The formation of vesicular horizons has been linked to these periods of abundant dust deposition (McFadden et al., 1998; Anderson et al., 2002). The distribution of pluvial lakes is one possible explanation for the difference in vesicular horizon expression between the cold and warm deserts of the Basin and Range Province. Pleistocene pluvial lakes occupied 27% of the area of cold deserts, but only 5% of the area of the warm deserts in the United States (extracted from map by Dutch, 1999). Consequently, sources of

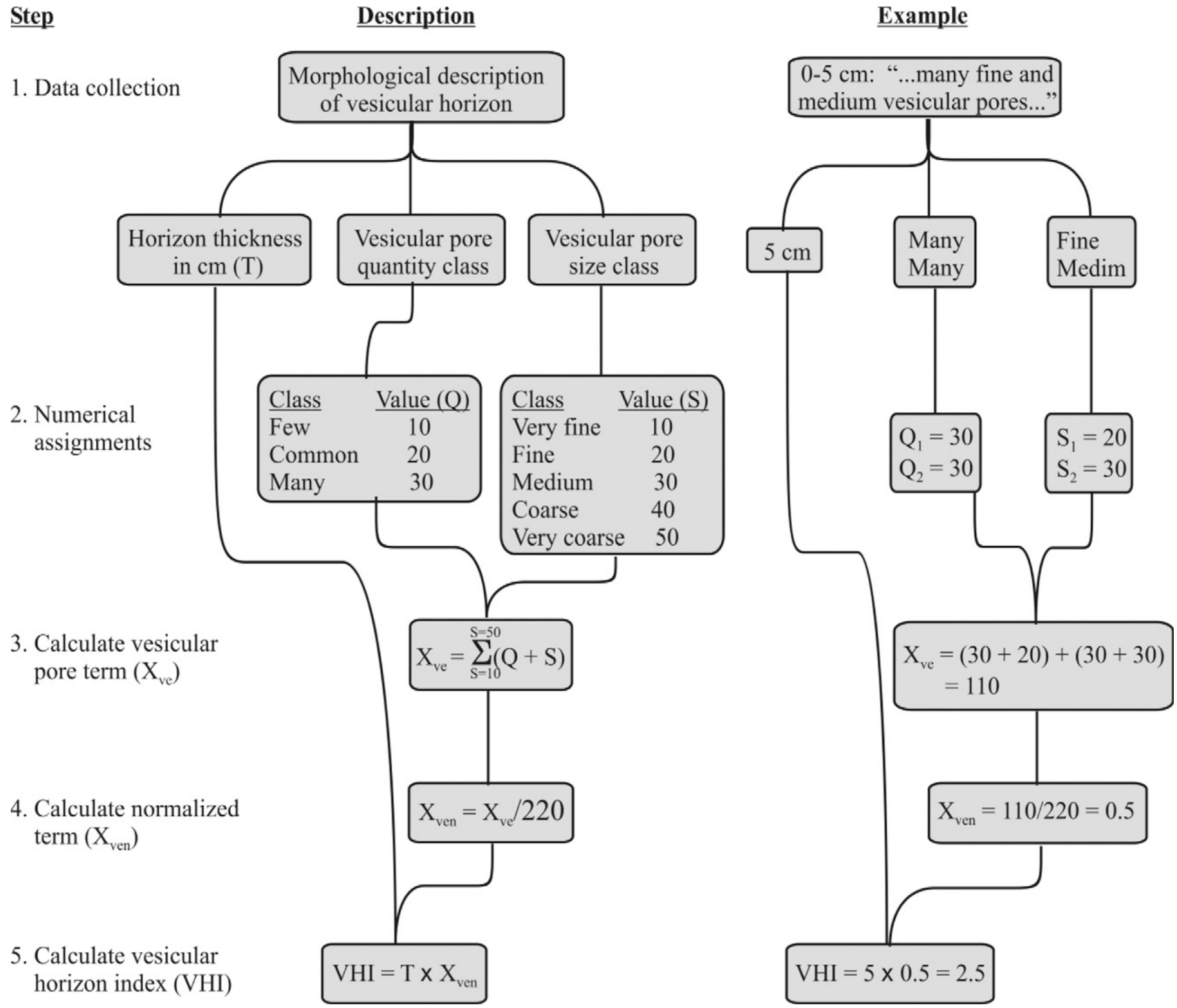

Fig. 7. Outline, description, and example of steps involved in calculation of the vesicular horizon index.

dust, which drives vesicular horizon formation, are much more extensive in the cold deserts.

The dynamic nature of vesicular horizons, as observed by some authors (Springer, 1958; Yonovitz and Drohan, 2009), suggests that some destruction and reformation of vesicular pores is likely to have occurred under modern climatic conditions. Vesicular porosity has been observed to increase with increasing number of wetting and drying cycles (Miller; 1971; Figueira and Stoops; 1983) and expansion of vesicular pores is commonly hypothesized to be driven by thermal expansion (Paletskaya et al., 1958; Evenari et al., 1974; Bouza et al., 1993; Henning and Kellner, 1994; Brown and Dunkerley, 1996; McFadden et al., 1998). With these mechanisms in mind, climatic records were analyzed to derive the annual number of wetting and drying cycles, as well as the average increase in temperature during drying. The frequency of wetting and drying cycles was found to increase along the gradient of ecoregions from the SON to the NBR (Fig. 10a), however high variability within each of the ecoregions means that the difference between the ecoregions was not significant according to ANOVA (p = 0.07). The modern climate may lead to greater vesicular horizon expression in the cold deserts due to the more frequent precipitation events, which offer more opportunities for vesicular pore formation and growth, but the high variability of precipitation frequency clouds the importance of this trend

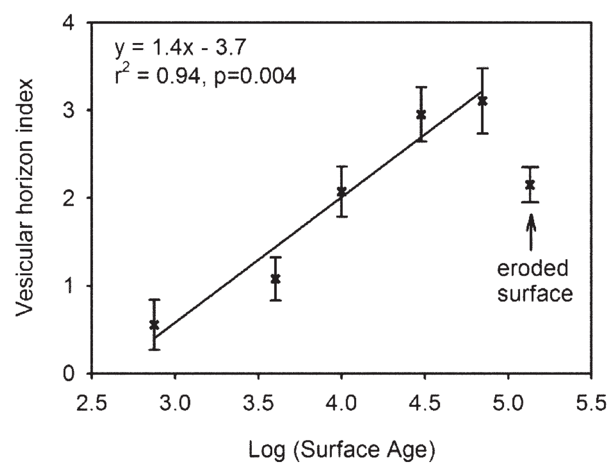

Fig. 8. Vesicular horizon index as a function of soil age on a chronosequence of alluvial fans in the Mojave Desert (McDonald, 1994). Error bars indicate one standard error.

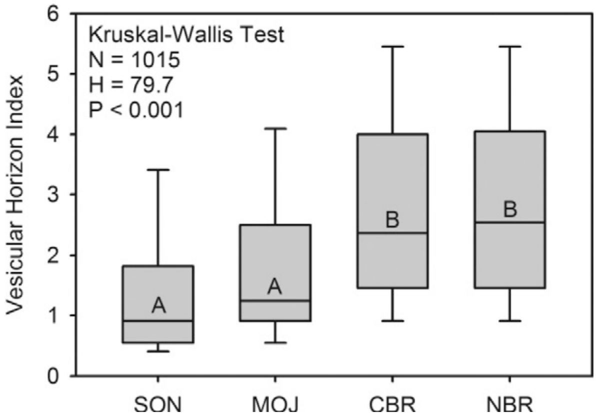

Fig. 9. Box plots of vesicular horizon index by Level III ecoregions (USEPA, 2006a): SON = Sonoran Basin and Range, MOJ = Mojave Basin and Range, CBR = Central Basin and Range, NBR = Northern Basin and Range. Boxes labeled with the same letter indicate a nonsignificant difference between groups, according to the Mann–Whitney test with a Bonferonni correction for multiple comparisons (per family α = 0.05, per test α = 0.008). Outliers are not shown.

relative to observed differences in VHI between the ecoregions. Average temperature increase during drying was actually lowest in the NBR, highest in the CBR, and intermediate in the SON and MOJ (Fig. 10b); This indicates that differences in thermal expansion do not likely explain the trend in vesicular horizon expression.

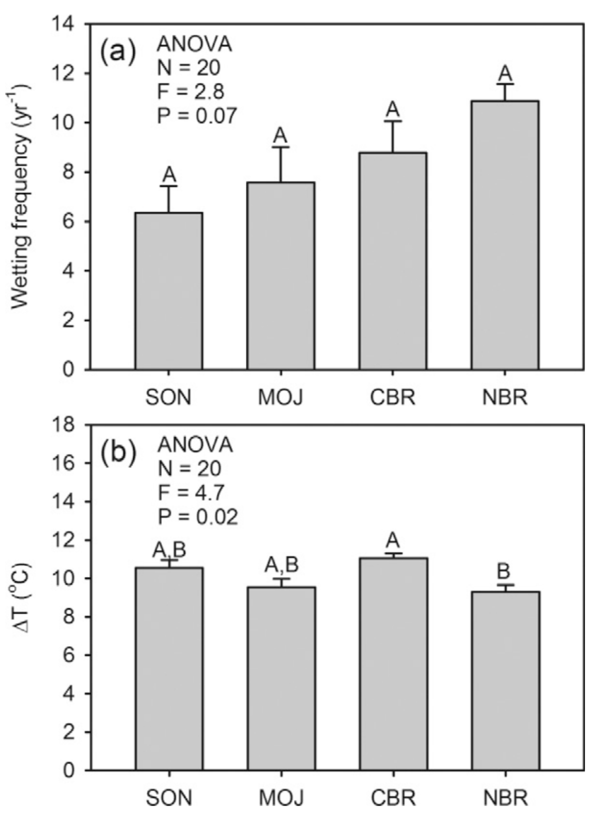

Fig. 10. Results of climate analysis grouped by ecoregion (SON = Sonoran Basin and Range, MOJ = Mojave Basin and Range, CBR = Central Basin and Range, NBR = Northern Basin and Range): (a) frequency of precipitation events resulting in wetting of the vesicular horizon and (b) increase in temperature during drying of the vesicular horizon (ΔT). Bars labeled with the same letter indicate a nonsignificant difference according to Tukey's test.

Biotic influences on vesicular horizon distribution include past and present vegetation types, burrowing animals, and biological soil crusts. Vesicular horizons are usually not observed, or are weakly expressed, in the undercanopy environment because of the increased activity of burrowing animals (Shafer et al., 2007) and protective canopy cover, both of which prevent surface sealing required for vesicular horizons formation (Evenari et al., 1974). Bare or clast-covered interspace soils that allow the formation of vesicular horizons are characteristic of desert scrub communities in both the hot and cold deserts (Eckert et al., 1978). In the Mojave Desert, vesicular horizons occur in three vegetation communities that occur with increasing elevation: creosote (840 m), blackbush (1400 m), and pinyon-juniper (1750 m), but do not occur in the higher elevation fir-pine forests (Amundson et al., 1989). Contrary to our findings, weaker expression of vesicular horizons was observed in the Great Basin steppe community that occurs at high elevations in the Mojave Desert (Quade, 2001). In that study, the weak expression of vesicular horizons in the high elevation zones was attributed to the disruption of desert pavement by vegetation advances during the last glacial maximum. However, subsequent studies in the Mojave Desert have suggested that desert pavements recover rapidly from disruption due to vegetation advances (Valentine and Harrington, 2006; Pelletier et al., 2007). Considering the rapid formation of vesicular pores under favorable conditions (Yonovitz and Drohan, 2009), it is also likely that vesicular horizons were only temporarily affected by past vegetation advances. Vesicular horizons have been observed to reform in plant scars, which are microtopographic features left by the death of long-lived perennial vegetation, even though these areas were mixed by burrowing animals that inhabited the undercanopy environment during the life of the plant (McAuliffe and McDonald, 2006). Given these considerations, differences in past or modern vegetation are unlikely to explain differences in vesicular horizon expression among the deserts of the Basin and Range Province. Vesicular horizons are observed across a range of plant communities, as long as bare interspace is present, and are unlikely to be significantly impacted by past vegetation advances that may have decreased or eliminated the bare interspace.

Biological soil crusts are a biotic factor that may have more direct influence on vesicular horizons. Biological soil crusts have been observed growing directly on vesicular horizons (Danin et al., 1998; Joeckel and Clement, 1999; Cantón et al., 2003). Moss-lichen crust can promote vesicular horizons formation by trapping dust (Williams et al., 2010). Biological soil crusts of the hot and cold desert display differences in morphology; having a prominent pinnacled microtopography in the cold deserts and a smooth microtopography and cryptic appearance in the hot deserts (Belnap et al., 2001). This difference in microtopography suggests a stronger dust-trapping capacity by the biological soil crusts in the cold desert, which could impact vesicular horizon formation.

Vesicular Horizon Index and Other Soil Properties

The median VHI was lowest in soils with hyperthermic temperature regimes, higher in thermic soils, and highest in mesic and frigid soils (Fig. 11a). Due to the smaller number of cryic soils, the median VHI was not significantly different from the other temperature regimes, except for the hyperthermic soils. The reason for the relationship between VHI and soil temperature regime cannot be evaluated from the purely observational data presented here. This relationship is difficult to separate from that described above between VHI and ecoregions of the Basin and Range Province. While both relationships suggest that vesicular horizons are better expressed in soils of colder environments, the relationship may be an artifact of another factor that influences vesicular horizon formation, such as the prevalence of pluvial dry lakes that act as dust sources in those areas.

Analysis of VHI by soil order shows that VHI is significantly higher in Aridisols and Mollisols compared to Inceptisols (Fig. 11b). The aridic moisture regime of the Aridisols, and most of the Entisols in the dataset, may explain why soils in these orders tend to have high VHIs. Vesicular horizons are better expressed in arid soils because of greater rates of dust deposition (McFadden, 1988; McFadden et al., 1998), exposure to cyclic wetting and drying (Springer, 1958; Miller, 1971; Evenari et al., 1974; Figueira and Stoops, 1983), and sparse vegetation cover, which allows more extensive surface sealing (Evenari et al., 1974). The high VHI of the Mollisols is contrary to the common perception that vesicular horizons are associated with low organic matter soils (Blackburn, 1975). The median organic C content of Mollisols in our data set is 1.5%, more than double the median organic C content for all of the soil orders in the dataset together (0.7%). The organic C content of the Mollisols with vesicular horizons is apparently not sufficient to stabilize aggregates and prevent formation of vesicular pores.

The median VHI is not significantly different among any of the most common vesicular horizon textures (Fig. 11c). The median VHI was slightly higher in soils with silt loam textures, but was not significantly different from the other commonly observed textures according to the statistical analysis. This result suggests that all of the most common textures observed in vesicular horizons (loam, sandy loam, fine sandy loam, very fine sandy loam, and silt loam) are equally conducive to vesicular horizon formation. Previous studies have demonstrated that vesicular porosity can form across a similar range of soil textures (Peterson; 1980; Yonovitz and Drohan, 2009). Coarser textures (e.g., sands and loamy sands) and finer textures (e.g., clay loams) are much less common in vesicular horizons (Fig. 6). Thus, coarse-textured parent material may require substantial alteration, typically through eolian additions, to allow vesicular horizon formation. On the other hand, extensive weathering and clay accumulation may lead to textures that are too clay-rich to support vesicular pore formation. This is thought to occur in some settings where eolian deposition allows the formation of a new vesicular horizon at the surface, while the buried vesicular horizon becomes increasingly enriched in clay and is transformed to a B horizon (McFadden, 1988).

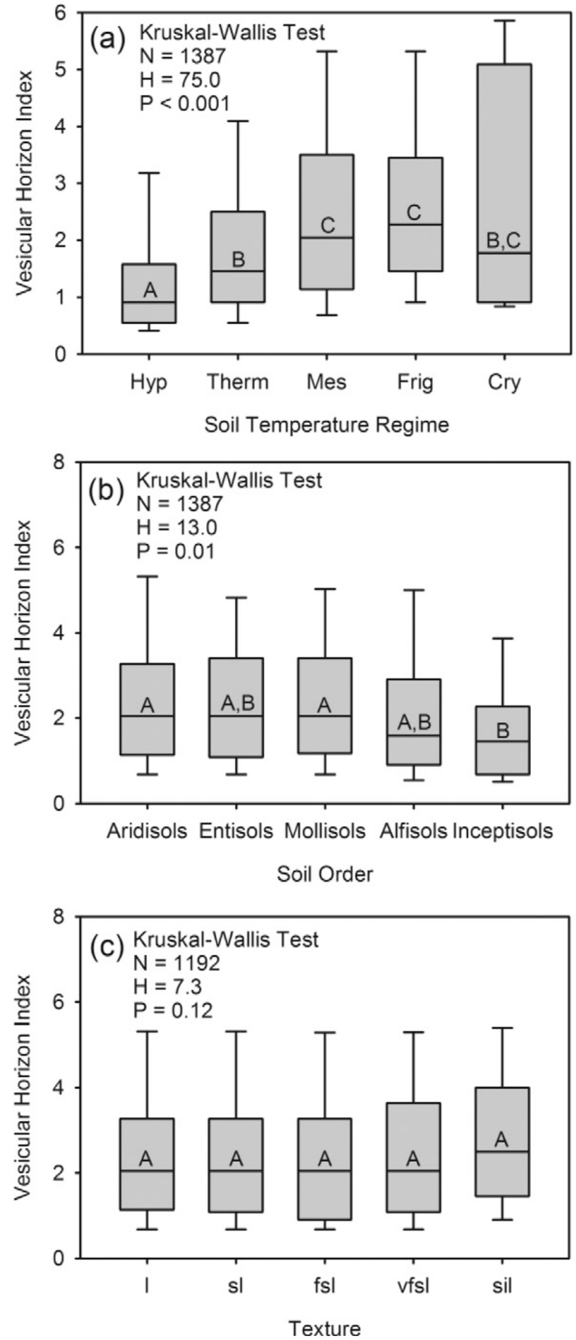

Fig. 11. Box plots of vesicular horizon index in soils grouped by: (a) soil temperature regime (Hyp = hyperthermic, Therm = thermic, Mes = mesic, Frig = frigid, Cry = cryic), (b) soil order, and (c) vesicular horizon texture (l = loam, sl = sandy loam, fsl = fine sandy loam, vfsl = very fine sandy loam, sil = silt loam). Boxes labeled with the same letter indicate a nonsignificant difference between groups, according to the Mann–Whitney test with a Bonferonni correction for multiple comparisons (per family α = 0.05, per test α = 0.005). Outliers are not shown.

SUMMARY AND CONCLUSIONS

Soil databases were used to analyze a large dataset, including 1387 soils with vesicular horizons, spanning the western half of the United States. We estimate that there are 156,000 km^2 of soils with vesicular horizons in the western United States, mostly within the arid Basin and Range Province. Vesicular horizons have highly variable chemical properties (organic C, electrical conductivity, ESP, pH, $CaCO_3$), reflecting the diversity of soil-forming environments in which they occur. The VHI, calculated from horizon thickness and size and quantity of vesicular pores, was developed and used to quantify vesicular horizon expression. Application of the VHI using the soil databases revealed that the strongest expression of the vesicular horizon occurs in the cold deserts (i.e., NBR and CBR ecoregions) and in soils with mesic and frigid temperature regimes. The association of strongly-developed vesicular horizons with cold soils may be due to a confounding factor, such as the large extent of pluvial dry lake beds that act as sources of dust in the cold deserts of the Basin and Range Province. Only weak associations were found between soil order and VHI, with the highest VHI occurring in the Aridsols and Mollisols. There was no significant difference in VHI among vesicular horizons with different textures (loam, sandy loam, fine sandy loam, very fine sandy loam, and silt loam). Other textures are rarely observed in the vesicular horizon. The cause of the trends presented here cannot be evaluated based on the observational methods used in this study, however, the results suggest hypotheses that may be tested experimentally in future studies.

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