Glacial dust in soils of Pennsylvania, USA: Evidence for an eolian component of fragipan horizons

Katherine Lindeburg[A]**,** Patrick Drohan[B], William Waltman[C], Austin Young[D], Mary Kay Lupton[E]

[A]Graduate student of Crop and Soil Sciences, Pennsylvania State University, University Park, PA, USA, Email ksl149@psu.edu
[B]Faculty of Crop and Soil Sciences, Pennsylvania State University, University Park, PA, USA, Email pjd7@psu.edu
[C]Educator of Horticulture and Agriculture, Pennsylvania State Coop. Extension, Coudersport, PA, USA, Email wjw15@psu.edu
[D]Staff of Crop and Soil Science, Pennsylvania State University, University Park, PA, USA, Email mxk397@psu.edu
[E]Student of Crop and Soil Science, Pennsylvania State University, University Park, PA, USA, Email aay5003@psu.edu

Abstract

Contributions of glacial dust (loess) to soils that result in a loess parent material and subsequent soil profiles imprint a unique geochemical signature and profile morphology. In areas where loess deposits are thinner, capping a differing parent material, or perhaps re-worked over time, identifying such polygenetic soils becomes more difficult. In this paper, we present preliminary results of a larger study of eolian additions to Pennsylvania soils and compare soils with fragipan subsoil horizons derived from pre-Wisconsinan and Wisconsinan glacial tills. Preliminary results suggest widespread eolian additions across both glacial periods, dust incorporation into parent materials of both soils prior to its formation, and dust inputs following fragipan formation. We suggest a general chronology of fragipan formation and degradation that explains the incorporation of loess into the soil profiles.

Key Words

Appalachians, pedogenesis, mineral aerosols, aeolian deposition

Introduction

The extent of wind-blown (eolian) surface additions to non-loessal soils is poorly documented for much of the Northeastern United States (N.E.U.S.). In the N.E.U.S., eolian deposits associated with the last glacial maximum (LGM) have assumed to be small, based on General Circulation Model (AGCMs) predictions of anticyclonic circulation and winds from the east and northeast (COHMAP Members 1988) and large distances from the Midwestern source regions. In contrast, patterns of loess distribution in the midcontinent and recent simulations of prevailing paleowinds from the west and north-west during last glacial period (Bettis III *et al.* 2003; Muhs and Bettis III 2000) suggest conditions conducive to dust transport from local sources and regional redistribution. Such paleoclimatic models are consistent with loess sequences in Pennsylvania (Carey 1978; Millette 1955) and observations of regional eolian deposits. Anomalously high silt contents in limestone and dolomite valleys (Cronce 1987), colluvial surface soils in the Ridge and Valley (Ciolkosz *et al.* 1986; Peterson *et al.* 1970), footslope colluvium (Hoover 1983), and ridge tops (Ciolkosz *et al.* 1990) have been attributed to widespread eolian deposition and interpreted alongside additional evidence for significant geomorphic alteration of unglaciated landscapes during glacial periods (Ciolkosz *et al.* 1986).

Background and overview

The site-specific, but limited evidence of thin loess deposition across the N.E.U.S. requires further documentation. A potential mechanism to evaluate the regional influence of loess to soils would be to tie loess deposition to a landscape feature also believed derived contemporaneously with loess deposition. If such a feature was found to have a loess signature, then the regional extent of such thinner loess deposits would allow for much greater precision in mapping loess deposition. The fragipan subsoil horizon is potentially such a signature feature. The origin of the fragipan is still a matter of debate (Smalley and Davin 1982, and references therein). At the centre of this debate are the origins of its silt rich content, density, brittleness, and prismatic structure, which generally are attributed to pedogenic (e.g., shrink-swell cycles; clay illuviation) (Carlisle 1954; Jha and Cline 1963) or geogenic (e.g., density inherited from parent material; rapid desiccation, collapse, and crack formation) (Assallay *et al.* 1998; Bryant 1989) processes. If geogenic, than the fragipan's polygonal structure and density are largely a relict feature of landscape instability, and likely derived at the end of a glacial event when loess deposition is typically widespread. Landscape movement of a moist to wet colluvial deposit, with loess incorporated during movement, resulted in eventual settling and desiccation of a silt rich horizon; settling and desiccation produced prisms and particle contraction enhancing density increases in the fragipan.

Research on chronosequences of soils with fragipans has shown that fragipan aging is associated with a reduction of prism circumference, increased distance between prism centres, reduction of prism bulk density, and an increased differentiation with depth in fragipan prism and face material (Waltman 1981). These observations suggest a mechanism for fragipan degradation over the course of pedogenesis and provide reasonable support that, to some degree, crack growth and infilling occur because of and alongside prism degradation. Nevertheless, explanations of how observed differences in particle size, mineralogy, and geochemistry of prism matrix and faces were derived in pedologically old soils are not entirely agreed upon.

Objectives of this study are (1) to evaluate the extent and spatial distribution of eolian materials in glacial till soils across time, and (2) to evaluate whether fragipan is largely a relict subsoil feature. We address the first objective and test our first main hypothesis—namely, that till parent materials of soils and their fragipans were augmented with glacial dust—with silt mineralogy and particle shape, morphology, and surface features of fine and very fine sands. We base this approach on others' observations that mineralogy, shape parameters, and geochemistry are useful in sourcing sediments (e.g., Muhs and Bettis III 2000) because (a) mineralogy of local sediments may be distinct from hypothesized exotic sources, and hence, mineralogy can fingerprint distinct sources; (b) particle shape and morphology of glacial and eolian transport mechanisms are distinct from each other (Krinsley and Doornkamp 1973); and (c) features of (a) and (b) are maintained over course of pedogenesis. Essentially, the mineralogical and/or particle morphological alterations due to pedogenesis can be distinguished as such and differentiated from original parent properties.

To test our second main hypothesis—namely, that formation of prismatic structural units and inter-prism cracks was contemporaneous with till parent material deposition and rapid desiccation—we infer timing of parent material deposition and crack initiation from extent and distribution of an eolian component within the soils. Dust provides a temporal constraint on parent material deposition, and possibly also, on timing of crack initiation and origin of its polygonal structure because (a) eolian deposition is temporally constrained by paleoclimatic conditions (glacial periods), and Holocene deposition can be assumed negligible; (b) spatial distribution (matrix vs. face and depth trends) of dust reflects original deposition rather than reorganization during pedogenesis; and thus, is interpretable within a temporal and mechanistic fragipan formation model.

Methods

Study sites

We selected representative fragipan soils of central Pennsylvania developed from tills of similar lithology but different ages (Waltman 1981). Parent material of a pedologically old soil (coarse-loamy, mixed, mesic Aeric Fragiaquult) is the pre-Wisconsinan (>70,000 YBP) White Deer till, comprised of siltstone, conglomerate, and minor amounts of limestone; a pedologically young soil (fine-loamy, mixed, mesic Aeric Fragiaquept) developed from Wisconsinan (12,500 to 15,000 YBP) Woodfordian till, comprised of gray siltstone, shale, and sandstone.

Soil characterization

Analyses were made on subsamples of archived fine-earth (< 2-mm) soil samples (Waltman 1981). Concentrations of major, minor, trace, and rare earth elements (REEs) were determined by lithium metaborate fusion and elemental analysis by X-ray fluorescence (XRF) at ALS Chemex (Sparks, NV). Sand and silt particle size fractions were isolated for particle morphological and mineralogical analyses according to standard techniques (Soil Survey Staff 2004). Fine sand (250 to 125 µm) and very fine sand (125 to 50 µm) fractions were separated through wet sieving of dispersed samples following organic matter removal. Grain shape, morphology, and surface features were characterized using grain mounts of fine and very fine sand particle size fractions viewed with a petrographic microscope and scanning electron microscopy (SEM). Particle shape analyses were performed using ImageJ freeware. Mineralogy was determined for random powder mounts of silt fractions (50-10 µm and 10-2 µm fractions) using X-ray diffraction (XRD) Jade software. Statistical analyses were computed using Minitab Inc.

Results

Particle shape and surface morphology

Fine and very fine sands are generally more angular and less round in the Wisconsinan than those in the pre-Wisconsinan soil. In the Wisconsinan fragipan horizons, matrix and faces have statistically indistinguishable sand shape factors. In contrast, within the pre-Wisconsinan fragipan horizons, matrix sands are significantly less angular, more round, and have a greater solidity index than the face sands (p-value <0.05).

Particle size distribution and mineralogy
In both soils, fragipan matrix soils have more clay than fragipan faces and non-fragic soils. Non-fragic soils have significantly (p-value <0.05) more coarse silts and less medium and fine sands than fragipan soils. In the pedologically old pre-Wisconsinan soil, an abrupt increase in sand and decrease in silt occurs with depth at the boundary between the non-fragic horizons (Ap, E, and Bw) and the fragipan horizons below 56 cm.

Plagioclase and K-feldspar are dominant minerals comprising ~40% of the silt fraction of surface soils, and decline with depth to ~15% in the pedologically young Wisconsinan soil. In contrast, feldspars in the pre-Wisconsinan profile are only minor, if at all, mineral constituents of silts. Interestingly, while essentially absent below 56 cm, both plagioclase and K-feldspars are present—albeit, in minor amounts—in the shallowest soils (Ap, E, and Bw horizons) in the pedologically old pre-Wisconsinan profile.

Elemental composition
The pre-Wisconsinan and Wisconsinan soils exhibit similar, systematic differences in major and minor, trace, and REEs in fragipan matrix and faces. Faces are consistently enriched relative to matrixes in Si, Zr, and Ti; faces are depleted in Al, Fe, Mg, Ca, Na, K, Mn, and P. Between pedons, the pre-Wisconsinan has more Si and less Mg, Ca, Na, K, Mn, P, and Ti than the Wisconsinan soil. Differences within the Wisconsinan are restricted to lateral gradients between matrix and faces of fragipans. In contrast, systematic depth trends occur in addition to lateral differences in geochemistry of pre-Wisconsinan fragipan matrix and faces. Distinct changes in normalized and absolute concentrations of REEs and immobile elements and abrupt decline in base cations below 56 cm suggest that the Ap, Bt1, Bt2, and IIBx1 horizons are dissimilar in origin than soils below, and likely, reflects lithologic discontinuity within the pre-Wisconsinan soil.

Discussion

The differences in physical properties and mineralogy within the Wisconsinan soil result from pedogenic processes during ~15 ky of development. Dominant soil forming processes include weathering of primary minerals of low stability, losses of elements associated with the weatherable primary minerals, residual enrichment of resistant minerals and associated elements, production of secondary minerals, and translocation out of colloids from zones of weathering to zones and accumulation at depth. The minor differences in particle shape metrics and surface morphological properties likely are due to pedogenesis rather than a difference in material provenance: Matrix sands are subtly rounder than face sands, though, from SEM analyses, we interpret a similar origin of angular particles for the matrix and faces, and the explain the observed differences by pedogenic processes (preferential destruction or masking of matrix sand angularity from amorphous siliceous surface coatings). Results from elemental analyses and REEs corroborate our interpretations of particle shape and SEM analyses, providing further support for the same original parent source of fragipan face and fragipan matrixes.

In contrast, differences within the pre-Wisconsinan soil suggest a complex formation history in which pedogenic processes may have been augmented with or replaced by geomorphic alteration during periods of environmental conditions different than those of the present. The older soil exhibits differences between the matrix and face sand grain features which could reflect effects of spatial heterogeneity of weathering intensity within the fragipan or relatively recent additions of mineral dust. The presence of feldspars in the upper, non-fragic soil horizons may reflect a period of eolian deposition and incorporation into the soil long after the initiation of pedogenesis and crack formation. Surface soils and face material of the shallowest fragipan horizon are all enriched in Zr and REEs relative to deeper soils; without exogenous additions, we would expect the depletion at the surface and a decline in depletion with depth. Geochemical and mineralogical results corroborate soil textural clues to a lithologic discontinuity below the first fragipan horizon and support a polygenetic model of soil formation in the pre-Wisconsinan soil.

Conclusion

The particle shape matrixes and angular surface features observed in both pedons from SEM and particle shape analyses are compatible with modeled origin as glacial sediment and redistribution following wind-transport and deposition either locally or within a moderate proximity from the original sediment source (Krinsley and Doornkamp 1973; Pye 1995). Nevertheless, we recognize the potential origin of sand angularity from solely glacial processes without eolian transport and thus, focus our current research efforts on distinguishing between the two transportation mechanisms.

References

Assallay AM, Jefferson I, Rogers CDF, Smalley IJ (1998) Fragipan formation in loess soils: Development of the Bryant hydroconsolidation hypothesis. *Geoderma* **83**, 1-16.

Bettis III EA, Muhs DR, Roberts HM, Wintle AG (2003) Last glacial loess in the coterminous USA. *Quaternary Science Reviews* **22**, 1907-1946.

Bryant RB (1989) Physical processes of fragipan formation. *Soil Sci. Soc. Am. J.* **24**, 141-150.

Carey JB (1978) The genesis and morphology of four soils developed in loess. Ph.D. diss., Pennsylvania State University.

Carlisle FJ (1954) Characteristics of soils with fragipans in a Podzol region. Ph.D. diss., Cornell University.

Ciolkosz EJ, Carter BJ, Hoover MT, Cronce RC, Waltman WJ, Dobos RR (1990) Genesis of soils and landscapes in the Ridge and Valley Province of central Pennsylvania. *Geomorphology* **3**, 245-261.

Ciolkosz EJ, Cronce RC, Sevon WD (1986) Periglacial features in Pennsylvania. Pennsylvania State University, Agronomy Series No. 92, University Park, PA.

COHMAP Members (1988) Climate changes of the last 18,000 years: Observations and model simulations. *Science* **241**, 1043-1052.

Cronce RC (1987) The genesis of soils overlying dolomite in the Nittany Valley of central Pennsylvania. Ph.D. diss., Pennsylvania State University.

Hoover MT (1983) Soil development in colluvium in footslope positions in the Ridge and Valley Physiographic Province of Pennsylvania. Ph.D. diss., Pennsylvania State University.

Jha PP, Cline MG (1963) Morphology and genesis of a Sol Brun Acide with fragipan in uniform silty material. *Soil Sci. Soc. Am. Proc.* **591**, 339-344.

Krinsley DH, Doornkamp JC (1973) 'Atlas of quartz sand surface textures.' (Cambridge University Press: London).

Millette JFG (1955) Loess and loess-like deposits of the Susquehanna River Valley of Pennsylvania and a section of the Laurentians in Canada. Ph.D. diss., Pennsylvania State University.

Muhs DR, Bettis III EA (2000) Geochemical variations in Peoria Loess of western Iowa indicate paleowinds of midcontinental North America during last glaciation. *Quaternary Research* **53**, 49-61.

Petersen GW, Ranney RW, Cunningham RL, Matelski RP (1970) Fragipans in Pennsylvania soils: A statistical study of laboratory data. *Soil Sci. Soc. Am. Proc.* **34**, 719-722.

Pye K (1995) The nature, origin and accumulation of loess. *Quaternary Science Reviews* **14**, 653-667.

Smalley IJ, Davin JE (1982) Fragipan horizons in soils: A bibliographic study and review of some of the hard layers in loess and other materials. In 'New Zealand Soil Bureau Bibliographic Report 30'. (Department of Scientific and Industrial Research: Wellington, New Zealand).

Soil Survey Staff (2004) Soil survey laboratory methods manual. (U.S. Gov. Print. Office: Washington, DC).

Waltman WJ (1981) Fragipan morphology in late Wisconsinan and pre-Wisconsinan age soils of Pennsylvania. M.S. thesis, Pennsylvania State University.