Range of Fragipan Expression in Some Michigan Soils: I. Morphological, Micromorphological, and Pedogenic Characterization

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ABSTRACT

Many of Michigan's loamy soils exhibit varying degrees of fragipan expression, which may be variously influenced by their parent materials. We examined three soils in northern Michigan with varying degrees of fragipan expression to assess development of fragipans formed in acidic and calcareous glacial drift. To accomplish this, soil characterizations were made through field, physical, chemical, and micromorphological observations and analyses. The soils have bisequal horizonation: an upper sequum associated with podzolization processes and lower sequum associated with lessivage. Protofragipans and fragipans are found only in the lower sequum. The soils experience periodic episaturation and contain at least one lithologic discontinuity, often near the protofragipan or fragipan. The protofragipan and fragipans have loamy sand to loam textures, weak platy to subangular blocky structure, higher bulk densities (1.5–1.9 g cm^{-3}) and lower pH values (4.8–6.8) than adjacent horizons, brittle failure, and fine vesicular pores. Eluvial protofragipan and fragipan horizons contain albic materials that tongue into underlying argillic horizons. Illuvial fragipans exhibit clay coats, flows, and bridging. Thin-section characterizations confirm the presence of closely packed fabrics, intergrain bridging by clays, and void pedofeatures. Scanning electron microscopy (SEM) provides evidence of eluviation, reorganization of silt and clay, fluctuating redox conditions, degraded void pedofeatures, and the presence of surficially amorphous (bonding) materials in the protofragipan and fragipans. Soil extraction data do not preclude the presence of a fragic-property (brittleness) agent. Results, therefore, indicate that these protofragipans and fragipans are pedogenic and can form, with variable expression, in both acidic and calcareous glacial parent materials.

Soils with fragipans are commonly found across northern Michigan, and all of these soil series also have (or allow for) bisequal horizonation. Michigan soils with fragipans also have spodic horizonation (e.g., E-Bs, E-Bh, or E-Bhs) in their upper sequum, while their lower sequum resembles Alfisols (e.g., E′-Bt). In these soils, the fragipan occurs in the eluvial or illuvial (or both) portion of the lower sequa. Rather than having strong fragipan character, some lower sequum horizons only exhibit fragic soil properties as defined by Soil Survey Staff (1999). Similar horizons, exhibiting only weakly expressed fragipan character, have been referred to as "protofragipans" (Lindbo et al., 1995; Ciolkosz and Waltman, 2000) or "incipient fragipans" (Grossman et al., 1959). As in other U.S. locales, soils with fragipans in Michigan are variable in their fragipan expression, development, or both.

In the Great Lakes region, fragipans are found in soils on both acidic and calcareous parent materials. In Michigan, however, fragipan horizons formed in acidic drift are far more common and spatially extensive than those formed in calcareous drift (Soil Survey Division, 2004). Because fragipans on acidic drift are more common and extensive in Michigan and the Great Lakes region, it seems reasonable that they may also be better developed than their calcareous counterparts. Such a question has not been addressed in the fragipan literature. Furthermore, only a few studies have explored the formation of soils with fragipans in Michigan (e.g., Yassoglou and Whiteside, 1960; Bockheim, 2003) despite the wide occurrence of these soils, and no studies have investigated the highly variable fragipan expression here. The purpose of this study was to evaluate the varying degree of fragipan expression in Michigan's soils and assess differences in development among fragipans formed in acidic and calcareous drift. The degree of fragipan expression in selected soils was characterized through morphological, physical, chemical, and microscopic observations and analyses, to elucidate their possible pedogenic pathways.

MATERIALS AND METHODS

Site Descriptions

Three soil series from Michigan representing different degrees of fragipan expression were chosen for study. The Feldhauser (coarse-loamy, mixed, active, frigid Oxyaquic Glossudalfs), Munising (coarse-loamy, mixed, active, frigid Alfic Oxyaquic Fragiorthods), and Glennie (coarse-loamy, mixed, superactive, frigid Oxyaquic Fraglossudalfs) series commonly exhibit weakly, moderately, and strongly expressed fragipans, respectively. Sampling sites were selected based on similar site characteristics and their distribution across northern Michigan (Fig. 1). All three sites have a cool, humid continental climate with mean temperatures ranging from −6.6 to −9.4°C in winter and 17.7 to 18.6°C in summer. Total annual precipitation ranges from 689 to 862 mm (NOAA/NCDC, 1961–1990). Presettlement and current vegetation at the sites is mixed, coniferous-deciduous forest. Forests at all three sites have experienced varying degrees of disturbance by logging, fire, and uprooting. All are located on Late Wisconsinan (ca. 14 to 10 ka) glaciogenic landforms largely formed of loamy to sandy glacial till. Periglacial processes following deglaciation, however, may have variably influenced soil genesis at each site. The sites chosen for description and sampling are located on geomorphically stable surfaces and are moderately well drained (Berndt, 1988; Werlein, 1998; Williams, 1998).

More specifically, the Feldhauser profile is located at a summit position on a landform assemblage called the "Grayling Fingers" (Schaetzl, 2002; Fig. 1). The parent material at this site consists of calcareous sandy loam till (>132-cm thick)

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Abbreviations: AAO, acid ammonium-oxalate; CD, sodium citrate-dithionite; RDP, related distribution pattern; SEM, scanning electron microscopy.

overlain by 28 cm of silts and fine sands (Werlein, 1998; Schaetzl, 2002). Sugar maple (*Acer saccharum* Marshall) and American beech (*Fagus grandifolia* Ehrh.) dominate the overstory vegetation. The Munising profile is located on an interfluve of the distal margin of the Sixmile moraine, in sandy loam, noncalcareous glacial till, and glaciolacustrine sediment (Doonan and Byerlay, 1973; Berndt, 1988; Fig. 1). Sugar maple, northern red oak (*Quercus rubra* L.), and ironwood [*Ostrya virginiana* (Mill.) K. Koch] dominate the overstory. The Glennie profile is located in a summit position on an interfluve of the Glennie moraine, where calcareous sandy loam and loam glacial till are the parent materials (Williams, 1998; Fig. 1). The overstory vegetation is dominated by aspen (*Populus tremuloides* Michx.), northern red oak, red maple (*A. rubrum* L.), eastern white pine (*Pinus strobus* L.), and black cherry (*Prunus serotina* Ehrh.).

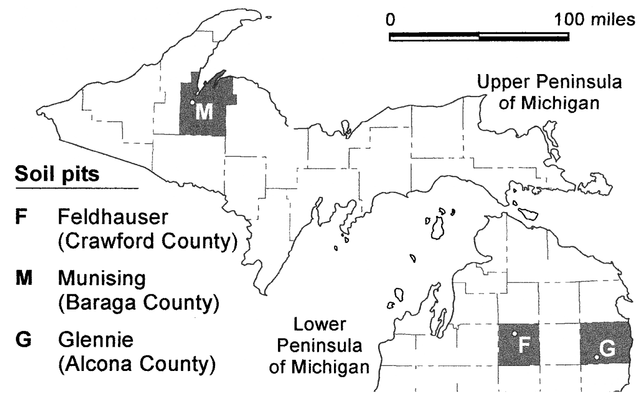


Fig. 1. Study area map showing the sampling locations for the Feldhauser, Munising, and Glennie pedons.

Field and Laboratory Methods

After sampling sites were identified, soil pits were dug by a backhoe. Physical setting and profile descriptions were conducted according to the Soil Survey Division Staff (1993) and Schoeneberger et al. (1998). Soil pit faces were first sketched and photographed and then genetic horizons were sampled. Samples were air-dried and sieved to remove coarse fragments (>2 mm). The remaining fine earth fraction was analyzed in the laboratory. Particle size distribution was determined by pipette with prior H_2O_2 pretreatment to remove organic matter for A, Bhs, and Bs horizons (Sheldrick and Wang, 1993). Sand separates were determined by dry sieving the sand fraction. The clay-free sand content was calculated and used to illustrate changes in the immobile particle fraction by horizon, which has been recommended for detecting lithologic discontinuities (Schaetzl, 1998). A 2:1 water/soil mixture was used to measure pH. Extractions for Fe, Al, and SiO_2 were performed on the <2 mm fraction of all genetic horizons using sodium citrate-dithionite [CD; Fe_d, Al_d, $(SiO_2)_d$] and acid ammonium-oxalate [AAO; Fe_o, Al_o, $(SiO_2)_o$] (Ross and Wang, 1993; Loeppert and Inskeep, 1996). Extracts were analyzed by flame atomic absorption spectrophotometry. Thick eluvial and illuvial parts of transitional horizons were extracted and analyzed separately. We interpreted the extraction data in the following way. Fe_d, Al_d, and $(SiO_2)_d$ represent noncrystalline and crystalline free oxide forms of Fe (Jackson et al., 1986; Dahlgren, 1994), and both Al and Si to a lesser extent (McKeague et al., 1971). Fe_o, Al_o, and $(SiO_2)_o$ represent noncrystalline (organically complexed and inorganic) forms of Fe (Farmer et al., 1983; Parfitt and Childs, 1988), and both Al and Si to a lesser extent (McKeague et al., 1971). Core samples were also collected from the soil pit face for bulk density analysis (Blake and Hartage, 1986). Genetic horizons thinner than the core sampler used were sampled in combination with the subjacent horizon. Triplicate bulk density values were calculated for each horizon or horizon pair, on an oven-dry, coarse-fragment-free basis and then averaged.

Microscopic Methods

Undisturbed bulk samples were collected from all protofragipan and fragipan horizons. Thin section samples for soil micromorphology were cut from samples collected from the pit face in 10 × 6.5 × 5 cm metal tins. These samples were impregnated with 3M Scotchcast (epoxy) resin under vacuum, and oven-cured at 40 to 50°C for 3 d. Oversized (38 × 75 mm) thin sections were cut and polished to a thickness of ≈30 μm (National Petrographic Service, Inc., Houston, TX). Thin sections were examined using a petrographic microscope in plane- and cross-polarized light, using temporary cover slips in immersion oil to aid viewing. Micromorphological descriptions were made according to Bullock et al. (1985). Digital images (micrographs) of selected micromorphological features (in plane-polarized light) were collected using a digital imaging system (Pixera Professional).

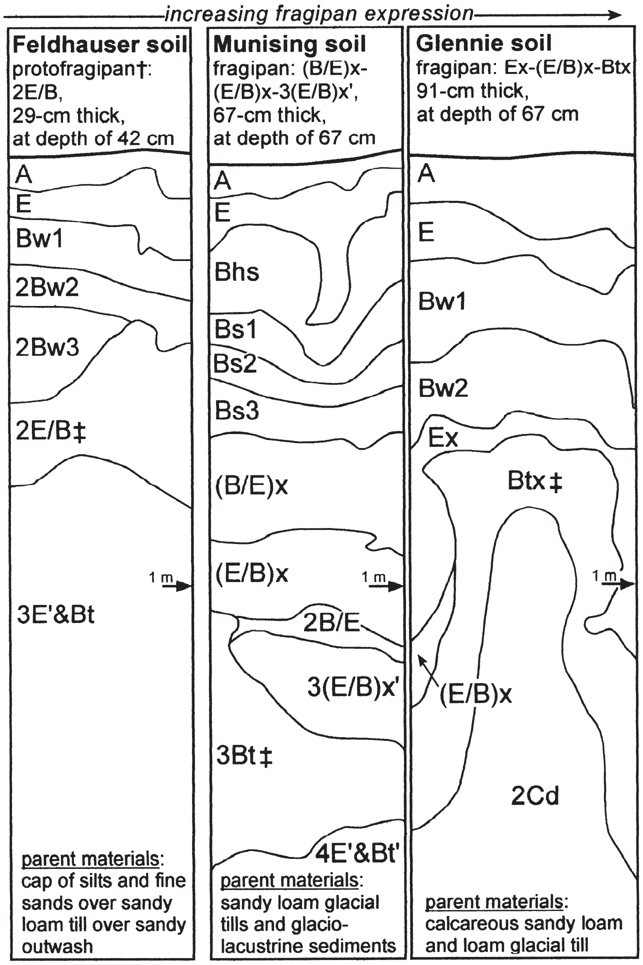
Intact clod samples, used for SEM imaging, were also collected. These were first divided by hand into subsidiary peds and then subdivided along planes of weakness under a stereographic microscope using a dissecting needle. Of the single, primary peds obtained, only a few, minimally disturbed representative samples were chosen for imaging. Each selected ped or subped sample was mounted onto an aluminum SEM stub using epoxy (Flegler et al., 1993). Carbon paste was used as the conducting medium between the top of the sample and the stub. Samples were then carbon and gold coated to reduce charging. The SEM observations and imaging were conducted on a JOEL JSM-6400V SEM (Joel Inc., Boston) equipped with a Soft Imaging System AnalySIS for image capture and analysis.

RESULTS AND DISCUSSION

Profile Descriptions

All three soils have bisequal horizonation with podzolization dominant in the upper sequa and clay illuviation in the lower sequa. Fragic soil properties (Feldhauser soil) or fragipans (Munising and Glennie soils) are found in the eluvial or illuvial portions of their lower sequa.

The upper sequum of the Feldhauser profile has albic and cambic horizons, both with weakly developed color and structure (Fig. 2; Table 1). The lower sequum contains a 2E/B and 3E′&Bt horizon whose Bt parts contain illuvial clay, particularly as intergrain bridges or lamellae. When dry (as at the time of sampling), the 2E/B horizon is notably brittle. This horizon exhibits fragic soil properties, but does not meet all of the additional fragipan criteria. Specifically, this horizon fails to meet these fragipan criteria: bodies of oriented clay and clay films as evidence of pedogenesis, ≥10 cm between structural units, and virtually no roots in ≥60% of horizon (Soil Survey Staff, 1999). Thus, we consider the 2E/B horizon a protofragipan due to its weakly expressed fragipan character. Soil structure is weakly developed and most of the horizons have loose to very friable consistence. Although we found no evidence of reduced soil matrices within the Feldhauser solum, the 2E/B



† "protofragipan": a horizon that exhibits fragic soil properties
‡ root-restrictive layer

Fig. 2. Profile sketches of the Feldhauser, Munising, and Glennie soils, which represent weakly, moderately, and strongly expressed fragipan horizons, respectively, in Michigan.

horizon exhibited common, faint, finely disseminated iron depletions. We found evidence of faunal- and floralturbation in the form of surficial worm casts and treethrow activity. Rooting appeared to be restricted in the 2E/B horizon.

The Munising upper sequum has an albic horizon and four spodic horizons, while the lower sequum contains transitional horizons that have both albic materials and fragipan characteristics (Fig. 2; Table 1). Lower sequum B horizons show evidence of illuvial clay accumulation as argillans, clay bridges and/or lamellae. The upper sequum horizons have moderately developed structure; structural development varies in the lower sequum. The fragipan and the 3Bt horizons have firm or very firm consistence; the remaining horizons have a loose to friable consistence. Redoximorphic features were observed in the lower sequum. Iron depletions are common in the E parts of the lower sequum horizons and contrasted either faintly or prominently with the surrounding Bt matrix. Iron concentrations, in the form of (a few) ferriargillans, occur in the Bt part of the 3(E/B)x′ horizons and 3Bt horizons. Pit and mound topography indicated that soil mixing by uprooting had occurred. Roots extend into the 3(E/B)x′ horizon, but are confined to channels and faces between structural units.

The Glennie upper sequum has albic and cambic horizons that have weakly developed color and structure (Fig. 2; Table 1). Both eluvial and illuvial horizons of the lower sequum exhibit strongly expressed fragipan characteristics. The B parts of the (E/B)x horizon and the Btx horizon have argillans and bridges of illuvial clay. The 2Cd horizon is massive, dense, and strongly effervescent. Overlying horizons have moderately well-developed structure. Upper sequum horizons are loose or very friable in moist consistence, whereas lower sequum horizons are firm or very firm. The lower sequum is dense and appeared to present an obstacle for both root growth and vertical water movement. Iron depletions and concentrations were observed in the lower sequum. Redox depletions occur in the form of both pigment and clay losses in the Ex horizon and the E part of the (E/B)x horizon, with colors that distinctly contrast with the parent material matrix. Redox concentrations in the Bt part of the (E/B)x horizon and the Btx horizon appeared in the form of ferriargillans on ped faces and vertical root channels. We found little evidence of pedoturbation. Very few root traces were found in or below the Ex horizon, but a few roots extended to the (E/B)x horizon along planes of weakness.

Based on field observations, key morphological properties of the protofragipan and fragipans tend to be distinctive to either the eluvial or illuvial horizons; transitional fragipan horizons have varying degrees of both. Predominantly eluvial fragipan horizons tend to lack clay coats/films and contain variable amounts of albic materials that eventually form glossic horizons. The eluvial protofragipan and fragipan horizons tend to have a high value (≥ 5) and low chroma (≤ 3) moist colors, which indicate moderate to strong eluviation. Moist consistence is firm. Tonguing of the eluvial fragipans' albic materials into the underlying (transitional or illuvial) fragipan horizon suggests eluvial fragipan horizons may contain zones of degradation within these bisequal sola. Predominantly illuvial fragipan horizons exhibit clay coats/films and flows on ped faces and vertical root channels. Clay bridging was observable between sand grains. Moist colors range from brown to reddish brown, and moist consistence is very firm. All protofragipan and fragipan horizons, however, exhibit brittle failure, fine vesicular pores, reduced root presence or root restriction, variable structure ranging from weak, thick platy to strong, coarse subangular blocky, and evidence of oxyaquic conditions, suggestive of periodic episaturation. For reasons we do not fully understand, all of the fragipans lacked the prismatic structure that is commonly used, but not required, as a distinguishing criterion. While coarse, bleached prism faces generally do not occur in eluvial fragipans, they are commonly associated with illuvial fragipans (Bryant, 1989). It is possible that the relatively coarse texture of our fragipans (Fig. 3) as also observed by Yassoglou and Whiteside (1960) or the periodicity and rapidity of profile wetting and drying may have influenced structural development in our soils

Table 1. Selected morphological descriptions and physical properties of pertinent horizons from each profile.

Horizon	Depth	Color; structure†; consistence (moist)	Sand 2000–53 µm	Silt 53–2 µm	Clay <2 µm	Sand separates‡ vcs	cs	ms	fs	vfs	Texture class§	Pedologic features
	cm		%									
Feldhauser soil (coarse-loamy, mixed, active, frigid Oxyaquic Glossudalfs)												
A	2–7	10YR 3/1; mod fine granular; very friable	57.9	34.6	7.5	1.7	11.3	33.7	9.0	2.3	sl	Ochric epipedon
E	7–19	10YR 5/2; mod fine granular; very friable	56.5	38.0	5.6	0.9	9.4	31.7	8.1	6.3	sl	Albic horizon
Bw1	19–28	10YR 4/4; mod fine granular; very friable	49.8	43.9	6.3	0.9	8.3	28.5	8.1	3.9	sl	Cambic horizon
2Bw2	28–36	10YR 5/6; sg; loose	83.9	13.2	2.9	1.9	14.9	51.7	13.7	1.8	ls	Cambic horizon
2Bw3	36–44	10YR 5/4; mod fine granular; very friable	65.5	30.9	3.5	0.5	10.3	39.8	10.4	4.5	sl	Cambic horizon
2E/B proto-fragipan	44–73	10YR 6/3 (E), 10YR 5/4 (Bt); mod very fine abk; firm & brittle	44.7	45.7	9.6	0.5	6.7	26.2	7.8	3.6	l	Glossic horizon; fragic soil properties; albic materials; root-restricting; common fine vesicular pores; RMF¶ observed; slakes
3E′&Bt	73–160+	10YR 5/3 (E), 7.5YR 4/6 (Bt); weak coarse sbk to sg, massive; very friable, very firm	92.2	2.9	4.9	1.4	12.8	57.9	18.0	2.1	s	Argillic horizon (Bt part); clay bridges between sand grains in the Bt
Munising soil (coarse-loamy, mixed, active, frigid Alfic Oxyaquic Fragiorthods)												
A and E	0–10	5YR 3/1 (A), 5YR 4/2 (E); mod fine to med granular; very friable, friable	54.1	39.3	6.7	0.8	3.8	13.8	17.0	18.7	fsl	Ochric epipedon (A); Albic horizon (E)
Bhs	10–28	5YR 3/3; mod fine sbk; very friable	65.2	32.2	2.6	1.8	3.2	13.5	19.9	26.8	fsl	Spodic horizon
Bs1	28–43	7.5YR 4/4; mod fine sbk; very friable	62.0	34.0	4.0	0.6	3.3	13.7	20.4	23.9	fsl	Spodic horizon
Bs2	43–52	7.5YR 4/6; mod fine abk; very friable	64.1	33.2	2.7	0.7	4.3	15.2	20.1	23.8	fsl	Spodic horizon
Bs3	52–66	7.5YR 5/4; mod fine abk; very friable	67.4	23.3	9.3	5.1	5.2	14.8	20.4	22.0	(gr) fsl	Spodic horizon
(B/E)x fragipan	66–93	2.5YR 4/4 (Bt), 7.5YR 7/2 (E); weak thick platy; very firm & brittle	Bt: 74.6	17.1	8.3	Bt: 1.0	4.0	17.4	26.0	26.2	(gr) fsl	Fragipan (transitional); glossic horizon; albic materials; very few faint red (2.5YR 4/6) clay films on ped faces and along vertical root channels; RMF observed; slakes
			E: 68.7	28.8	2.5	E: 1.7	4.1	16.9	23.2	22.8	(gr) fsl	
(E/B)x fragipan	93–120	5YR 5/2 (E), 5YR 4/3 (Bt); weak thick platy; firm & brittle	E: 81.2	16.2	2.5	E: 2.2	4.6	21.2	26.5	26.7	(gr) ls	Fragipan (transitional); glossic horizon; albic materials; few faint reddish brown (2.5YR 4/4) clay films in pore spaces; clay bridging sand grains; very few fine vesicular pores; RMF observed; slakes
			Bt: 72.7	22.3	5.1	Bt: 2.5	5.0	20.8	25.5	19.0	(gr) fsl	
2B/E	120–127	5YR 5/4 (Bt), 5YR 5/2 (E); single grain; loose	93.6	5.3	1.0	1.8	5.3	33.4	38.9	14.2	(gr) s	Cambic horizon; glossic horizon; interfingering of albic materials; clay coatings on some sand grains; RMF observed
3(E/B)x′ fragipan	127–140	5YR 5/2 (E), 5YR 4/3 (Bt); mod med abk; firm & brittle	74.0	23.8	2.2	1.6	4.5	20.3	26.5	21.0	(gr) ls	Fragipan (transitional); glossic horizon; albic materials; few faint reddish brown (2.5YR 4/4) clay films in pores; clay bridging sand grains; very few fine vesicular pores; RMF observed; slakes
3Bt	140–168	2.5YR 4/4; strong very coarse abk; very firm	69.4	23.8	6.8	1.8	4.0	19.3	25.7	18.6	(gr) fsl	Argillic horizon; few prominent reddish brown (2.5YR 4/4) clay films around gravels and cobbles; RMF observed
4E′&Bt′	168–362	5YR 5/2 (E), 2.5YR 4/6 (Bt); sg, massive; friable	E: 96.0	3.0	1.0	E: 2.5	14.2	46.5	26.7	6.1	s	Albic horizon (E); argillic horizon (Bt); bands are 1–3 cm thick and spaced 4–15 cm apart; RMF observed
			Bt: 89.7	7.1	3.2	Bt: 0.9	4.5	35.1	36.1	13.1	s	
4C	362+	5YR 5/2; sg; loose	96.6	2.5	0.9	7.0	27.4	46.1	11.5	4.5	cos	
Glennie soil (coarse-loamy, mixed, superactive, frigid Oxyaquic Fraglossudalfs)												
A	2–16.5	10YR 3/2; mod fine granular; loose	11.2	84.0	4.8	1.3	6.8	39.7	28.1	8.0	ls	Ochric epipedon
E	16.5–24	10YR 5/3; mod fine granular; very friable	12.9	85.0	2.1	1.8	9.3	41.7	25.8	6.3	ls	Albic horizon
Bw1	24–40	10YR 4/6; mod med sbk; very friable	11.0	87.5	1.5	3.7	8.4	40.7	27.6	7.1	s	Cambic horizon
Bw2	40–69	10YR 5/6; mod med sbk; very friable	8.2	90.1	1.7	1.5	7.9	40.4	31.5	8.9	(gr) s	Cambic horizon
Ex fragipan	69–116	10YR 5/3; strong med sbk; firm and brittle	12.8	83.5	3.6	1.2	6.7	35.3	30.4	9.9	ls	Albic horizon; fragipan (eluvial); common fine vesicular pores; RMF observed; slakes
(E/B)x fragipan	116–141	10YR 5/3 (E), 7.5YR 4/4 (Bt); strong coarse sbk; very firm and brittle	17.5	69.0	13.5	1.0	5.2	26.5	25.0	11.3	sl	Glossic horizon; fragipan (transitional); albic materials; common fine vesicular pores; RMF observed; slakes
Btx fragipan	141–160	7.5YR 4/4; strong coarse sbk; very firm & brittle	16.5	55.1	28.4	1.5	4.0	22.5	19.1	8.0	scl	Argillic horizon; fragipan (illuvial); root-restricting; many prominent reddish brown (5YR 4/4) clay films and flows on vertical faces of peds; clay bridging sand grains; common fine vesicular pores; RMF observed; slakes
2Cd	160+	5YR 4/4; massive; firm	30.6	50.3	19.1	0.9	3.7	20.0	16.3	9.5	(gr) l	Strongly effervescent

† mod, moderate; med, medium; abk, angular blocky; sbk, subangular blocky; sg, single grain.
‡ vcs, very coarse sand (2000–1000 µm); cs, coarse sand (1000–500 µm); ms, medium sand (500–250 µm); fs, fine sand (250–125 µm); vfs, very fine sand (125–53 µm).
§ gr, gravelly; cos, coarse sand; s, sand; ls, loamy sand; sl, sandy loam; fsl, fine sandy loam; scl, sandy clay loam.
¶ RMF, redoximorphic features.

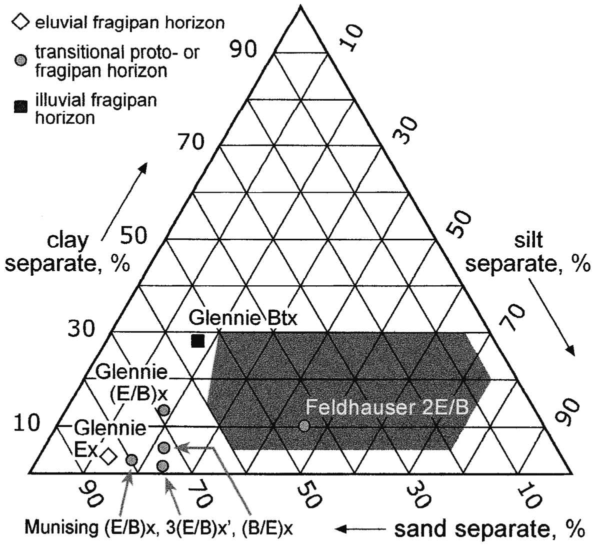


Fig. 3. Textures of protofragipan and fragipan horizons. Gray area represents the fragipan textural class developed by Peterson et al. (1970) for Pennsylvanian fragipan horizons formed in glacial till.

(Bryant, 1989; Chadwick and Graham, 2000). We are aware, however, of fragipans near the Munising profile that exhibit strong, coarse prisms with bleached faces.

Physical Properties

Sand fractions dominate all three profiles (Table 1). Medium sand is predominant in the Feldhauser and Glennie profiles, while the Munising profile shows a coarsening downward trend from very fine to medium sand. Clay or silt or both fractions tend to increase in the protofragipan and fragipan horizons.

Surface textures are loamy (i.e., loamy sand to sandy loam), and textures for deepest horizons are sand or loam (Table 1). In general, most fragipan parent materials are either loamy (Hallmark and Smeck, 1979; Soil Survey Staff, 1999) or texturally heterogeneous (Olson and Hole, 1967). The protofragipan and fragipans studied here are loamy sand, sandy loam, sandy clay loam, or loam in texture (Table 1; Fig. 3). Predominantly illuvial fragipans are finer textured than are their eluvial counterparts. While the protofragipan and fragipans studied tend to have sandier textures (Fig. 3) than fragipans in Pennsylvania (Peterson et al., 1970), other authors have reported similar textures (loamy sand, sandy loam, and loam) for fragipans formed in glacial drift (Yassoglou and Whiteside, 1960; Hallmark and Smeck, 1979; Veneman and Bodine, 1982; Habecker et al., 1990; Miller et al., 1993). Illuvial fragipans with even finer textures have also been reported (DeKimpe et al., 1976; Hallmark and Smeck, 1979; Habecker et al., 1990).

Clay-free sand data were calculated to identify lithologic discontinuities (Table 2; Schaetzl, 1998), which are thought to influence fragipan evolution (Habecker et al., 1990; Van Vliet and Langohr, 1981). Smeck et al. (1989) observed that fragipans in Ohio form in association with weathering discontinuities, which can form near or at lithologic discontinuities. Each profile has at least one lithologic discontinuity close to its protofragipan or fragipan based on trends in clay-free sand and coarse-fragment contents (Table 1).

All protofragipan and fragipan horizons have higher bulk density values than their overlying horizons and their subjacent horizons or parent material (Table 2), which is consistent with trends previously reported (e.g., Lindbo and Veneman, 1989, 1993; Miller et al., 1993). The bulk density values for the protofragipan or fragipan horizons of the profiles range from 1.5 to 1.9 g cm^{-3}, which is consistent with others formed in glacial drift (Yassoglou and Whiteside, 1960; Miller et al., 1971; Habecker et al., 1990). The increased bulk density of the protofragipan and fragipans clearly has not solely been inherited from the parent material.

Chemical Properties

In the three profiles, pH values are relatively low in the eluvial portion of each sequum and increase with depth (Table 2). Beneath the fragipan or protofragipan in the lower sequum, pH increases and reaches a maximum in the deepest horizon. Miller et al. (1993) found that the fragipan horizons, on average, had lower pH values than overlying and underlying horizons. Similarly, most protofragipan and fragipan horizons in this study have pH values lower than their overlying and underlying horizons, ranging from 4.8 to 6.8, despite the acidic or calcareous nature of the parent material. These values are similar to other fragipans formed in glacial drift: 4.6 to 6.5 (Yassoglou and Whiteside, 1960; Ransom et al., 1987; Miller et al., 1993).

According to the Soil Survey Staff (1999), pH values for fragipans beneath spodic horizons are often high relative to other fragipans. This trend, however, was not observed. The protofragipan and fragipan in the Feldhauser and Glennie profiles, both Alfisols, have higher pH values than the fragipan in the Munising (Spodosol) profile. The explanation for this trend lies in the nature of the parent materials. The Munising pedon has formed in acidic glacial drift, whereas the Feldhauser and Glennie soils formed in calcareous parent materials.

Soil extraction data have been used to interpret dominant pedogenic pathways and processes, and to evaluate the nature of fragipans. Some fragic properties, such as brittleness and the ability to slake (possibly due to the solubility of particle-binding/bridging agents) have been attributed to the presence of free- or combined-oxide forms of Fe, Al, and Si (Veneman and Lindbo, 1986; Norfleet and Karathanasis, 1996; Duncan and Franzmeier, 1999). Thus, increased extractable values of Fe, Al, or Si in fragipan horizons can be used as evidence of a possible causative agent(s) (e.g., Harlan et al., 1977; Hallmark and Smeck, 1979; Karathanasis, 1989; Norfleet and Karathanasis, 1996). Failure of extractable values to increase in the fragipan may imply the lack of such agent(s) (e.g., Wang et al., 1974; DeKimpe et al., 1983; Miller et al., 1993).

In all three profiles, $Fe_d > Fe_o$, indicating that most of the Fe in these profiles exists in free-oxide (noncrystalline or crystalline) forms. Values of $Al_o > Al_d$ in the

Table 2. Selected physical and chemical laboratory data for each pedon.

Horizon	Depth	Clayfree sand	Bulk density	pH	Fe_d	Al_d	$(SiO_2)_d$	Fe_o	Al_o	$(SiO_2)_o$
	cm	%	g cm^{-3}		g kg^{-1}†					
Feldhauser soil (coarse-loamy, mixed, active, frigid Oxyaquic Glossudalfs)										
A	2–7	62.6	nd‡	5.5	3.39	1.07	0.75	1.90	1.28	1.15
E	7–19	59.8	1.1¶	5.4	2.17	0.41	0.48	1.26	0.56	0.58
Bw1	19–28	53.2		5.6	6.07	1.87	0.69	4.41	2.32	0.35
2Bw2	28–36	86.4	1.4¶	5.8	1.73	0.85	0.78	1.36	1.22	1.15
2Bw3	36–44	68.0		5.9	2.96	1.11	0.82	1.31	1.96	0.38
2E/B	44–73	49.4	1.6	5.6	4.20	0.91	0.80	1.50	1.39	0.34
3E′&Bt	73–160+	97.0	1.7	5.9	1.07	0.40	0.74	1.18	0.86	BDL§
Munising soil (coarse-loamy, mixed, active, frigid Alfic Oxyaquic Fragiorthods)										
A and E	0–10	57.9	1.0	4.3	2.51	0.51	0.61	1.42	0.73	0.92
Bhs	10–28	66.9	1.0¶	5.0	5.76	4.57	1.37	4.86	6.06	0.83
Bs1	28–43	64.6		5.3	4.77	3.53	1.00	3.52	4.43	0.61
Bs2	43–52	65.9	1.1¶	5.5	5.49	4.25	1.19	4.10	5.24	0.46
Bs3	52–66	74.3		5.6	2.96	2.16	0.80	1.92	3.29	0.84
		Bt: 81.4			Bt: 3.83	0.38	0.97	1.91	0.84	BDL§
(B/E)x	66–93	E: 70.5	1.9	4.8	E: 1.88	0.44	0.59	0.80	0.94	0.60
		E: 83.3			E: 2.07	0.14	0.29	0.73	0.28	0.66
(E/B)x	93–120	Bt: 76.6	1.8	5.0	Bt: 2.43	0.19	0.88	1.07	0.34	0.28
2B/E	120–127	94.6	nd‡	5.5	1.80	0.17	0.57	0.70	0.30	0.16#
3(E/B)x′	127–140	75.7	nd‡	6.0	0.88	0.16	0.41	0.82	0.36	1.02
3Bt	140–168	74.5	1.7	5.6	3.25	0.20	1.20	1.09	0.45	0.19#
		E: 97.0			E: 1.32	0.16	0.83	0.82	0.28	0.86
4E′&Bt′	168–362	Bt: 92.7	1.7	6.0	Bt: 1.62	0.21	0.93	0.86	0.44	0.39
4C	362+	97.5	nd‡	6.3	2.39	0.15	0.84	1.31	0.28	0.19
Glennie soil (coarse-loamy, mixed, superactive, frigid Oxyaquic Fraglossudalfs)										
A	2–16.5	88.2	1.1¶	5.5	1.51	0.47	0.50	0.76	0.58	0.15
E	16.5–24	86.8		5.3	0.94	0.36	0.39	1.10	0.52	0.35
Bw1	24–40	88.8	1.4	6.3	4.48	1.75	0.94	3.39	2.76	1.50
Bw2	40–69	91.7	1.5	6.8	2.03	0.94	0.85	1.13	1.62	1.08
Ex	69–116	86.7	1.5	6.6	0.86	0.24	0.42	0.90	0.41	0.18
(E/B)x	116–141	79.7	1.7	6.5	3.73	0.47	1.29	1.02	0.77	0.89
Btx	141–160	76.9	1.6	6.8	7.17	1.12	3.37	1.81	1.69	0.26
2Cd	160+	62.2	1.4	8.0	4.16	0.58	2.27	0.93	0.71	1.39

† Multiply values in g kg^{-1} by 0.1 to convert to % dry soil.
‡ nd, no data.
§ BDL, below detection limit.
¶ Horizons sampled together.
\# Datum based on one measurement; replicate was below the detection limit.

profiles suggest that active, noncrystalline (organically complexed and inorganic) forms of Al also are dominant. Examination of the extraction data for Fe and Al reveals a few notable trends that are consistent with the findings of others (i.e., Blume and Schwertmann, 1969). In nearly all cases, maximum extractable values for Fe and Al are in the uppermost B horizon (e.g., Bw1 or Bhs). The position of these maxima suggests that podzolization (and associated subprocesses, such as chelation and cheluviation) is active and is responsible for the translocation of Al accompanied by Fe or organic matter or both and the relative enrichment of SiO_2 in the overlying eluvial zone. While the upper sequa are the loci of (advanced) podzolization within these sola, the lower sequa are associated with lessivage. Thus, there are no obvious associations among CD- and AAO-extractable oxides and noncrystalline forms of Fe, Al, and Si and the protofragipan/fragipan character of the horizons. These data, however, do not preclude the presence of a fragic-property (brittleness) agent that contains these elements in combination.

Micromorphological Properties

A number of micromorphological features have been consistently observed in thin sections from fragipans: (i) close-packing or interlocking of skeleton grains, (ii) sepic fabric (similar to a porphyric-related distribution pattern [RDP]), (iii) intergrain bridging by clay or amorphous silica, (iv) oriented clay in the form of grain, ped, or channel argillans (grain, aggregate, or void coatings) or pedotubules (infillings), and (v) degraded argillans (coatings) in close proximity to, or within the fragipan. In SEM samples, commonly described micromorphological properties of fragipans are closely packed fabrics, intergrain bridging, and intact and degraded void coatings. All protofragipan and fragipan horizons observed in thin section and under the SEM showed evidence of these properties.

Protofragipan and fragipans described in thin section exhibit a closely packed groundmass that is largely uninterrupted by voids, has a porphyric-RDP and massive microstructure (Fig. 4A). Payton (1993a) also reported closely packed, interlocked grains with a porphyric-RDP and massive microstructure in fragipan horizons. Micromorphological evidence of close-packing or interlocking of grains has been observed by others working with fragipans in glacial (Yassoglou and Whiteside, 1960; DeKimpe and McKeague, 1974; Lindbo and Veneman, 1993; Miller et al., 1993) and other parent materials (Thompson, 1980; James et al., 1995). Moreover, these authors attributed fragipan hardness or consistence to close-packing or interlocking of mineral grains. We ob-

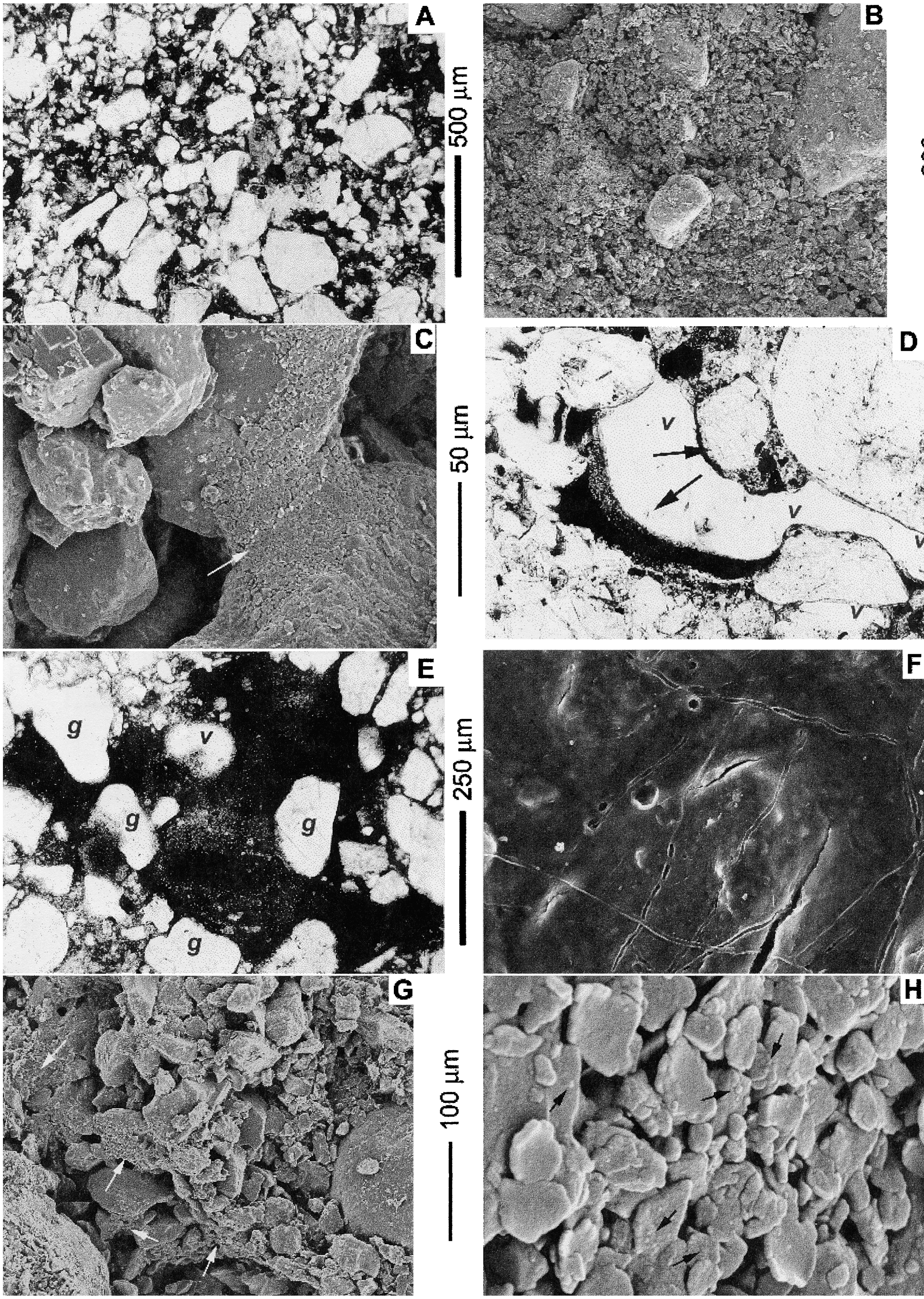


Fig. 4. Micrographs (A, D, E) and SEM images (B, C, F, G, H) of select micromorphological features of protofragipan and fragipan horizons. (A) Glennie (E/B)x close-packing (close porphyric related distribution pattern and massive); (B) Feldhauser 2E/B closely packed fabric (sand grains are closely packed with relatively clean very fine sand, silt, and clay-sized particles; voids are primarily packing voids); (C) Glennie Ex, intergrain bridge (composed of silt [and some clay-sized particles] between sand grains; silt grains and clay platelets are oriented; bridge is ≥60 μm thick); (D) Munising (B/E)x void coating ([gray grainy] void coating; crescentic; limpid clay, impure clay; 50–125 μm; layered); (E) Glennie (E/B)x void infillings ([gray grainy] void infilling; dense incomplete; silty clay; 100–250 μm; compound); (F) Feldhauser 2E/B plan view of a void coating (smooth-surfaced void coating of surficially amorphous, clay-sized material; linear features in image may be root or fungal hyphae traces); (G) Feldhauser 2E/B plan view of degraded void coatings (remnants of void coating composed of silt grains and clay-sized particles; void groundmass predominantly consists of very fine sand and silt; void is channel-like in morphology; at a larger scale, surficially amorphous, clay-sized material appears to discontinuously coat silt grains and clay-sized particles of the degraded coating and groundmass; mechanism for coating degradation cannot be determined based solely on this image); (H) Glennie (E/B)x surficially amorphous material (mostly silt grains, and clay-sized particles or clay minerals [or both] with a discontinuous, bead-like coating of a surficially amorphous, clay-sized material <1 μm in diameter).

served closely packed fabrics in all SEM samples of the protofragipan and fragipans (Fig. 4B), as did Thompson (1980) and Payton (1983).

While bridging of coarse grains by silty clay or dusty clay coatings (Bullock et al., 1985) was observed in thin section for each protofragipan and fragipan, it was best observed in the SEM samples (Fig. 4C). These meniscus-like bridges are composed of, or coated with, a clay-sized material that appears to be amorphous based on its surface morphology or composed of oriented clay-sized particles or clay minerals. Other bridges are larger, composed primarily of silt-grains with some clay-sized particles, and variable degrees of orientation. Intergrain bridging has frequently been observed and reported for fragipans using SEM (e.g., Bridges and Bull, 1983; Norton et al., 1984; Payton, 1983, 1993a; Lindbo and Veneman, 1989, 1993). By itself or in conjunction with closely packed fabrics, intergrain bridging may be associated with fragipan hardness or consistence (Knox, 1957; Yassoglou and Whiteside, 1960; DeKimpe et al., 1976; Payton, 1993a).

Void coatings (Fig. 4D) and infillings (Fig. 4E) were documented in thin section in each of the protofragipan and fragipan horizons. Void coatings are either typic or crescentic and composed of limpid, dusty, or silty clay, silt, or unsorted separates of various sizes. They range in thickness from 5 to 2000 μm with internal fabrics that are nonlaminated, microlaminated, layered, or compound. Void infillings are dense and either completely or incompletely filled with soil separates having similar compositions as those associated with void coatings. The most prominent void infillings, however, are composed of silty clay with a gray, grainy appearance. This material was observed filling voids up to 2 mm wide, and exhibited a variety of internal fabrics. Both clay-sized particles and silt (sometimes with sand) have been documented as infilling fragipan voids, as homogeneous fabrics (Yassoglou and Whiteside, 1960; DeKimpe and McKeague, 1974; Langohr and Pajares, 1983; Miller et al., 1993) or heterogeneous fabrics (Collins and O'Dubhain, 1980; Payton, 1983; Thompson and Smeck, 1983).

Some of the void coatings and infillings associated with the predominantly eluvial protofragipan and fragipan horizons exhibit a gray, grainy appearance (Fig. 4E). Collins and O'Dubhain (1980) reported that silt concentrations, best developed in fragipan horizons, exhibit a similar appearance in some Irish Spodosols. These silt concentrations were determined to be illuvial, oriented, very densely packed with no pore space, and sometimes microsorted void coatings and infillings. Ransom et al. (1987) observed the alteration of argillans to grainy cutans in a fragipan horizon in Ohio, which, along with extensive albic neoskeletan formation, were indicative of argillic-horizon degradation. Gray, grainy clay coatings in the upper portion of a fragipan, studied by Payton (1993a, 1993b), were associated with the deposition of Fe-depleted clay and very fine silt and are sometimes manifested as compound, illuvial coatings, as they may incorporate silt coatings and Fe coatings. According to Payton (1993b), clay illuviation under oxidizing conditions was followed by the mobilization of Fe oxides. Further changes in fragipan redox potential were associated with void-wall and clay-coating destabilization and degradation. Bleached clay and silt particles along these surfaces then became available for translocation via water (i.e., lessivage and pervection [Frenot et al., 1995], respectively), resulting in void surfaces exhibiting skeletal residues. Our observations suggest this may be occurring in eluvial zones of the protofragipan and fragipans.

Void-coatings and void-coating degradation were also observed in the protofragipan and fragipans using SEM (Fig. 4F, 4G). According to Payton (1993b), remnant coating patches become smaller and more isolated as the coating degrades. The few, isolated remnants of the channel coating (composed predominantly of silt with some clay-sized particles) in Fig. 4G suggest that it has experienced advanced degradation, which may eventually lead to channel-wall destabilization and the remobilization of the adjacent fabric. Although degradational features in fragipans have been reported in the literature, they have been evidenced mostly in thin sections or macromorphological investigations (Langohr and Pajares, 1983; Payton, 1983; Lindbo and Veneman, 1993; Miller et al., 1993; Lindbo et al., 2000; McDaniel et al., 2001).

Lessivage, pervection, and eluviation of Fe may be involved in the degradation of the void coating and fine- and coarse-material migration and microerosion (Payton, 1993b). Additionally, the association of silt with degraded coatings (Fig. 4G) and the silt accumulations discussed earlier suggest that water flow has influenced the migration and organization of the protofragipan or fragipan horizons' mobile components (i.e., plasma) (Langohr and Pajares, 1983; Payton, 1993a). Other mechanisms for the destabilization and translocation of silt within horizons such as fragipans are rapid wetting of dry soil, rapid dewatering of saturated soil, thawing of frozen soil, or access to a silt-rich source (Nettleton et al., 1994). Deposition of these grains is favored by pore-size discontinuities, low Ca and Mg content, high silt content, low organic carbon content, and low aggregate stability (Nettleton et al., 1994), many of which are common in the fragipans.

Void coatings composed of clay-sized material that appears to be amorphous based on its surface morphology were observed in protofragipan and fragipan horizons (Fig. 4H). This clay material is often in the form of micrometer-sized beads that is sometimes coalesced into larger aggregates. Although similar material has been reported as being associated with intergrain bridges (Payton, 1983), it has not (to our knowledge) been documented in electron micrographs of fragipan void coatings. Compositional data for this amorphous material was not collected due to its thin, discontinuous nature.

CONCLUSIONS

While fragipans are found in soils on both acidic and calcareous parent materials in Michigan, those formed in acidic drift are far more common and spatially extensive than those formed in calcareous drift (Soil Survey Division, 2004). It seems reasonable that those formed in acidic drift may also be better developed than their calcareous counterparts in Michigan. The purpose of this study was to evaluate fragipan expression in Michigan's soils and assess differences in development among fragipans formed in acidic and calcareous drift. This paper provides physical, chemical, and micromorphological data for three Michigan soils that exhibit varying degrees of fragipan expression, but generally similar site and solum characteristics, to elucidate their possible pedogenic pathways.

Three soils with varying degrees of fragipan expression from across northern Michigan were chosen for characterization. The Feldhauser soil, formed in sandy loam glacial till with a finer-textured cap, contains a protofragipan: a 2E/B horizon with fragic soil properties. The Munising soil, formed in sandy loam glacial drift, contains a moderately developed fragipan: (B/E)x, (E/B)x, 3(E/B)x′. The Glennie soil, formed in dense loamy glacial till, contains a strongly developed fragipan: Ex, (E/B)x, and Btx. All four soils have bisequal profiles and have similar seasonal hydrologic characteristics.

A few inferences concerning possible pedogenic pathways for fragipan evolution can be based on the data presented. In the three soils studied, the sola have been sufficiently acidified for the initiation of subsequent pedogenic processes. The upper sequum appears to be the locus of (advanced) podzolization and associated subprocesses (e.g., chelation and cheluviation) and translocation of silts and clays, which have guided the differentiation of the upper eluvial–illuvial horizon pair. The lower sequum, containing the protofragipan or fragipan horizons, appears to be the locus of lessivage (and pervection, to an extent), which have contributed to differentiation of the eluvial and illuvial portions of the protofragipan or fragipan. The lower sequum appears to also be affected by seasonal episaturation, at or above the protofragipan or fragipan, and associated saturation and reduction processes, which enhance the eluvial portion of the lower sequum and the degradation of the illuvial fragipan.

Closely packed fabrics, intergrain bridges, void coatings and infillings, and degraded void pedofeatures were observed in the protofragipan and fragipans studied. The presence of a fragic-property (brittleness) agent was not precluded by CD- and AAO-extraction data.

Data presented illustrate that the degree of fragipan expression in Michigan soils is not entirely controlled by the amount of carbonates in the parent material. Furthermore, our findings may have wider applicability within the Great Lakes region: an area in which studies of fragipan genesis are few.

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