PROPERTIES AND CLASSIFICATION OF MINERAL SANDS MINE SOILS IN SOUTHEASTERN VIRGINIA[1]

Z.W. Orndorff[2], W.L. Daniels, and J.M. Galbraith

Abstract. Significant areas of prime farmland in the upper Coastal Plain of Virginia have been disturbed by heavy mineral sands (Ti/Zr-bearing ilmenite, rutile, zircon) mining over the past 7 years. Previous work has shown that separation of sandy particles (tailings) from finer particles (slimes) in dewatering pits leads to significant lateral variability in the soils. The objectives of this study were 1) to characterize the chemical, morphological and physical properties of these mine soils and 2) to classify these soils. Thirteen soil profiles, ranging in age from 2 to 6 years, were described and sampled to 2 m. Samples were analyzed for particle size distribution, pH, exchangeable bases, exchangeable acidity, extractable Al, and organic matter (OM). The plow layers, which in most cases included topsoil, fertilizer, lime, and biosolids additions during reclamation, ranged from 10 to 24 cm in depth. These horizons were typically loamy sands and sandy loams with OM ranging from 0.2 to 1.5% and pH ranging from 5.6 to 8.0. Subsurface horizons were typically sands, loamy sands, sandy loams, sandy clay loams, and clays with lower pH, (< 5.5) low OM (< 0.5%), and low plant-available nutrients. Some profiles were relatively consistent in the subsurface, or changed only gradually with depth. Others contained adjacent dissimilar layers with abrupt horizons in between, such as alternating sands and clays. Several profiles contained dissimilar materials within a horizon, expressed as banded materials or as clayey fragments within a sandy matrix. Many profiles exhibited overturned stratification that we refer to as "convoluted banding" and may prove to be a diagnostic feature of some mineral sand mine soils. Heavy compaction was indicated in most profiles by the presence of densic layers in both loamy and clayey materials. The thirteen profiles were classified according to Soil Taxonomy into 4 subgroups, including one Fluventic Dystrudept, two Typic Udifluvents, three Typic Quartzipsamments, and seven Typic Udorthents.

Additional Key Words: Densic horizon, slimes, soil profiles, reclamation, titanium, tailings

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Introduction

In 1997, Iluka Resources Inc. (formerly RGC USA Inc.) began active mining of the 2000 ha Old Hickory deposit of heavy mineral sands (Ti and Zr in ilmenite, leucoxene, rutile and zircon) in the Upper Coastal Plain of Virginia (Berquist and Goodwin, 1989; Carpenter and Carpenter, 1991). The fluvio-marine terrace deposit lies in Dinwiddie and Sussex Counties (Fig. 1) in a relatively undissected landscape of Pliocene to perhaps early Pleistocene age (5.3 to 1.6 mya). The heavy minerals are contained within the upper 5 to 20 m of highly weathered Coastal Plain soils lying abruptly over Piedmont igneous and metamorphic saprolites. Similar deposits have been located and leased for future mining in Greensville County, Virginia (Brink Deposit), and at multiple locations in North Carolina. Since much of this area is prime farmland there is considerable interest in the effect of the mining operation on soil properties.

Knowledge of the mining process is important in understanding the characteristics of these mine soils. Where topsoil is being salvaged, existing vegetation is removed and approximately the upper 15 cm of A horizon material is bulldozed into windrows around the edges of the mining pits, and commonly becomes a portion of the enclosing dikes. Additional low-grade subsoil material is utilized to build enclosing dikes up to 4 m high. Mineral-enriched weathered

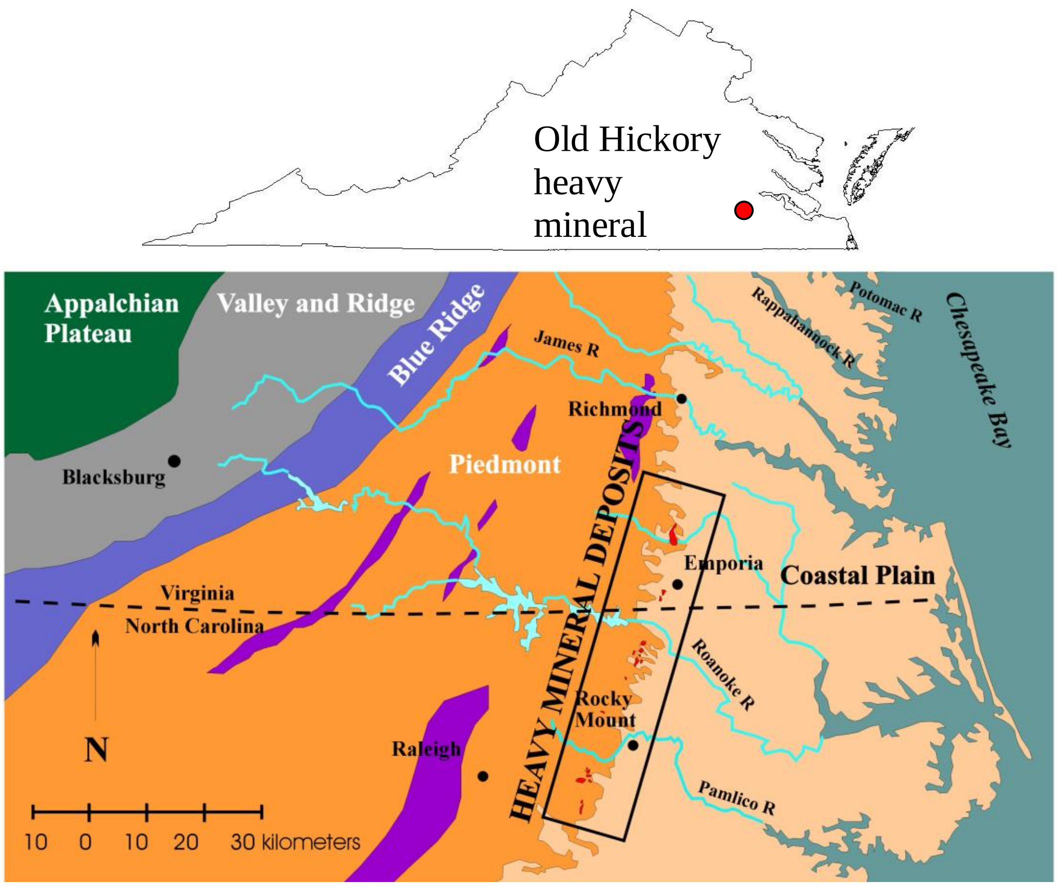

Figure 1. Location of Old Hickory heavy mineral sands deposit in Virginia and regional occurrence of heavy mineral sands.

soil and underlying Coastal Plain sediments are dry-excavated using conventional loaders and haulers, screened, and then mixed with water into a slurry and pumped to the wet separation (concentrator) facility. The slurry is then passed through sequences of cyclones and separatory spirals where the fine textured clays, silts, and some very fine sands (collectively referred to as slimes) are separated away from the heavier sand fraction. On average, the deposit generates from 35% to 45% slimes. The heavy mineral sands (particle density $\geq$ 4.0 g/cm^3) are further separated from the lighter Fe-coated host quartz (tailings) via spirals. No additives or chemicals are used in the separatory process.

The slimes are partially dewatered in a thickener via the addition of polymer flocculants and pumped with the tailings back to the reclamation pits in a water slurry at 35 to 50% solids. The majority of the the clay in the slimes fraction is Fe-coated kaolinite, but significant amounts of hydroxy-interlayered vermiculite and smectites do occur in some of the less weathered soils found in wetter and younger landscapes across the deposit, which negatively affect slime flocculation when encountered (Van Wormhoudt, 1993).

At varying times between 1997 and 2000, tailings and slimes were pumped either combined or separately to various excavation pits to dewater as discussed below. However, due to mixing and shearing in pumping from the thickener to the receiving pits, the slimes were re-dispersed when they discharged. This led to significant segregation of sand tailings “beaches” or fans immediately below the discharge points with finer textured silts and clays moving freely with water away from the discharge point (Fig. 2). Surface water was decanted as quickly as possible from the pits and returned to the processing plant as make-up water. In recent years, the company has utilized multiple internal dikes and water control structures within dewatering pits to minimize lateral separation of the slimes away from the tailings. For various operating reasons in 1997/1998, certain pits were backfilled with dominantly sandy tailings (e.g. 9801) while others (TP 1 and 2) received higher components of slimes. Regardless, re-dispersion of the slimes has led to a significant swell factor in the overall mining removal and tailings deposition process, and the resultant landscapes are frequently higher than original grade. Settling with time is also expected for these areas, particularly as the high water containing slimes dewater fully, but this has not been rigorously documented to date.

Depending on weather conditions, it took between several months to one year for the surface of the pits to dry down sufficiently to support machinery. Once accessible, the surface contour of the dewatered pits was graded with a bulldozer to ensure adequate surface drainage. Areas of highly contrasting materials were mixed with track loaders and dozers to the best extent possible. This was often accomplished by dozing/ramping the enclosing dike materials up and over the final reclamation surface. Next, agricultural lime (4 to 10 Mg/ha) was applied depending on texture and pH, and P-fertilizer was applied at 350 kg/ha P_2O_5.

Depending on revegetation sequence, certain pits also received an additional 150 to 200 kg/ha P_2O_5 when indicated by low soil test P. These bulk soil amendments were then incorporated via a sequence of chisel-plowing and/or offset disking. The overall goal of this combined treatment was to physically loosen, raise the pH and P levels of the mine soil materials to a depth of at least 30 cm. If topsoil was retained and accessible in the lateral dikes it was returned at varying thickness over the conditioned subsurface materials, and mixed in with a disk. Biosolids (75 Mg/ha) were incorporated over most of the pit surfaces. Additional N-P-K fertilizers were then added to the final reclamation surface as appropriate for the intended revegetation mixture, which has been mixed hayland/pasture (*Festuca arundinacea, Triflium pratense*, etc.) to date. Virginia Division of Mineral Mining (VDMM) regulations require two growing seasons of quality vegetative cover to meet permit release standards.

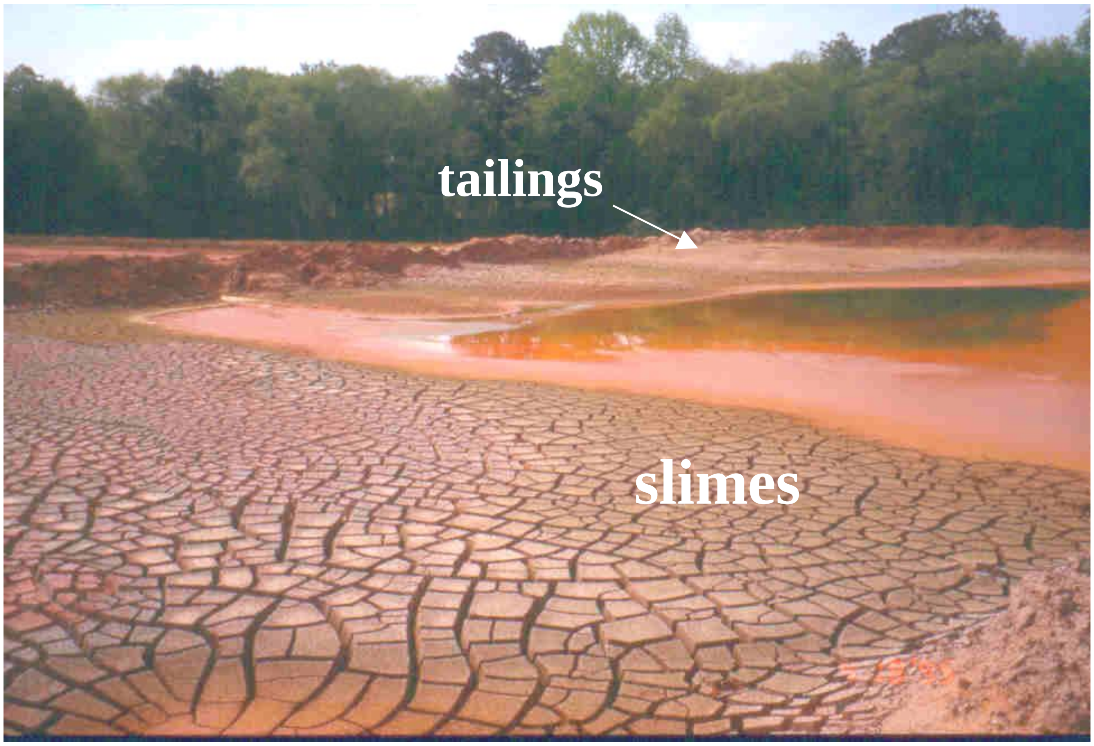

Figure 2. Strongly contrasting particle size in these materials is usually due to differential settling of tailings directly adjacent to discharge point (background) versus slimes that move with the discharge waters and settle at some distance away from the discharge pipe (foreground). This leads to extreme lateral variability in the subsurface if measures are not taken to limit segregation via internal diking or physical mixing after the tailings ponds dry down.

Previous work has shown that separation of tailings from slimes in dewatering pits leads to significant differences in soil texture, seasonal wetness and bearing capacity across the reclamation surfaces (Daniels, 2003). Schroeder (1997) detailed mine soil morphology and rooting in a limited set of small scale mining test pits at this site, but to date, no detailed study of the morphology of these mine soils as they occur on actual reclaimed mined lands has been reported. The objectives of this study were 1) to characterize the chemical, morphological and physical properties of these mine soils and 2) to classify these soils.

Materials and Methods

Thirteen representative mine soils from four mining pits were described and sampled to 2 m in backhoe pits in June, 2004. The locations of these pedons are shown in Fig. 3. The soils ranged in age from two to six years since reclamation. Soil profile descriptions were completed including horizon depths and designations, color, structure, consistence, rooting depths, and any other noteworthy morphological features. Samples were collected from each major morphological soil horizon from each pedon. Dissimilar materials were distinguished in the field descriptions, but they were not separated out in sampling. Therefore, laboratory analyses reflect the results for a composite sample of all materials within a horizon.

In the laboratory, samples were air-dried, ground to pass a 2-mm sieve, and analyzed for pH in a 1:1 soil to water slurry, organic matter (Walkley and Black, 1934), C and N using an Elementar Vario Max CNS analyzer, particle size distribution by the pipette method, and exchangeable Ca, Mg, K, Al and H. Cation exchange capacity (CEC) was determined by the summation of extractable Ca, Mg, K and exchangeable H and effective CEC (ECEC) was determined as the sum of extractable bases plus KCl-extractable Al. Based on previous studies by our group, exchangeable Na was assumed negligible. Unless otherwise noted, all methods were based on Methods of Soil Analysis Part 1 (Klute, 1986) and Part 3 (Sparks, 1996).

Results and Discussion

The soil profiles were highly variable among and within the mining pits studied. Soil materials varied distinctly not only among described horizons, but also within horizons. With few exceptions, the sampled pedons exhibited A-C horizonation. Only one pedogenically-developed horizon (Bw) was observed, as well as two buried A horizons. The thirteen profiles were classified according to Soil Taxonomy (Soil Survey Staff, 2003) into 4 subgroups, including one Fluventic Dystrudept, two Typic Udifluvents, three Typic Quartzipsamments, and seven Typic Udorthents (Table 1). Four representative profiles are shown in Fig. 4 – 7. Descriptions of these four profiles are presented in Tables 2, and some of their physical and chemical properties are presented in Table 3.

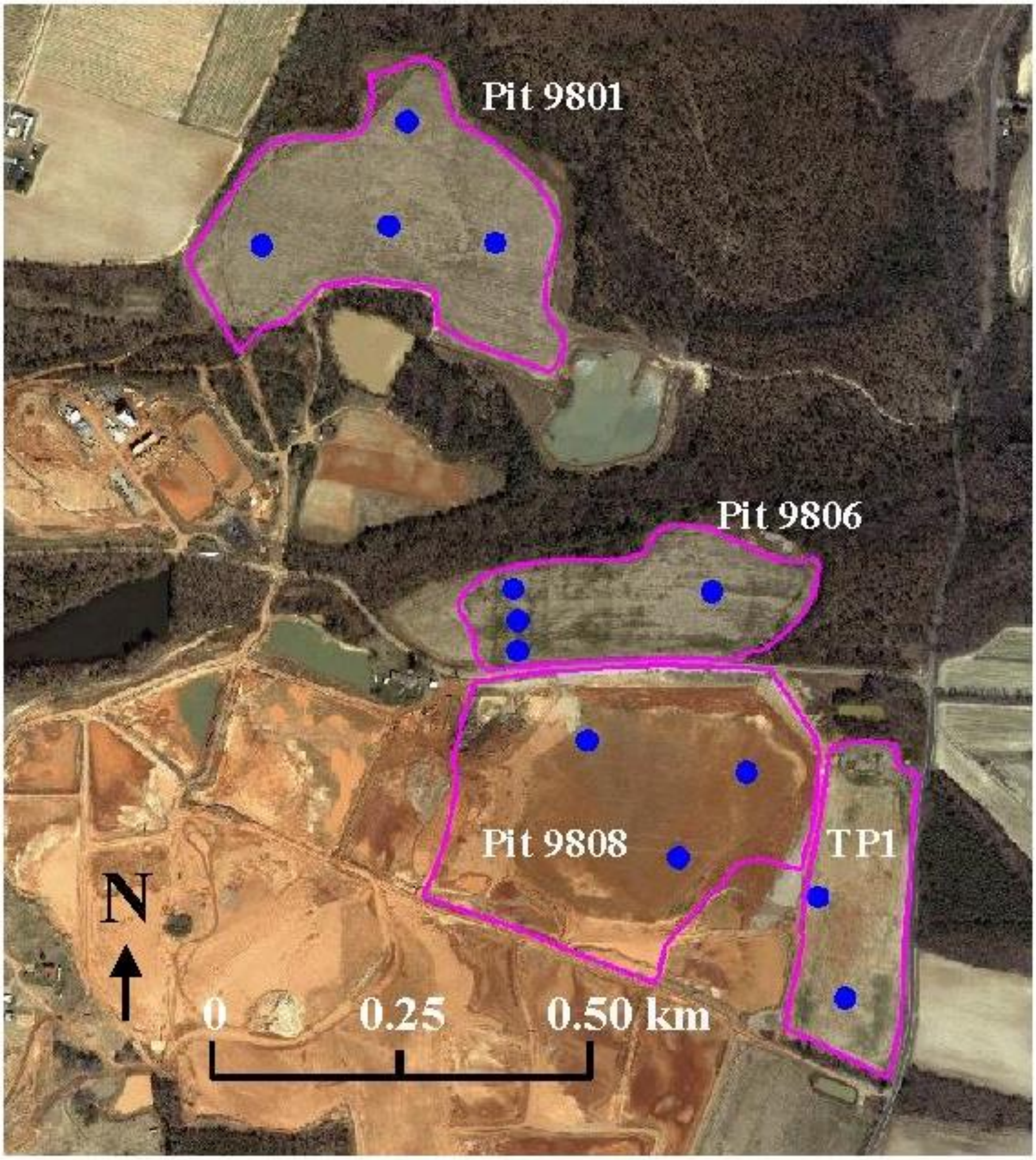

Figure 3. Location of 13 heavy mineral sand mine soils, from four reclaimed mining pits, that were described and sampled in this study.

Table 1. Classification of thirteen mineral sand mine soils.

Profile	Family
9801-4	fine-loamy over sandy or sandy-skeletal, aniso, mixed, thermic Fluventic Dystrudept
9808-3	sandy over clayey, aniso, mixed, non-acid, thermic Typic Udifluvent
TP1-1	loamy, mixed, non-acid, thermic, shallow Typic Udifluvent
9801-1	thermic, uncoated Typic Quartzipsamment
9801-3	thermic, uncoated Typic Quartzipsamment
9806-1	thermic, uncoated Typic Quartzipsamment
9801-2	sandy, siliceous, thermic Typic Udorthent
9808-1	loamy, mixed, non-acid, thermic, shallow Typic Udorthent
9806-2	loamy, mixed, non-acid, thermic Typic Udorthent
9806-3	loamy, mixed, non-acid, thermic, shallow Typic Udorthent
9806-4	loamy, mixed, non-acid, thermic, shallow Typic Udorthent
9808-2	loamy, mixed, non-acid, thermic, shallow Typic Udorthent
TP1-2	loamy, mixed, non-acid, thermic, shallow Typic Udorthent

Figure 4. Profile 9801-1 is a Typic Quartzipsamment as indicated by lack of pedogenic horizonation and the presence of sandy subsoil horizons, without excessive rock fragments, to a depth of at least 100 cm. Note the prominent color change between adjacent horizons at 19 cm.

Figure 5. Profile 9801-4 is a Fluventic Dystrudept as indicated by weak development of a pedogenically-altered horizon (Bw) and an irregular decrease in organic C between 25 - 125 cm. Strongly contrasting particle size classes and prominent color change between adjacent horizons are evident at 52 cm. A close up of the alternating bands of tailings and slimes below 140 cm is shown in Fig. 8.

Figure 6. Profile 9808-3 is a Typic Udifluvent, as indicated by lack of pedogenic horizonation in the subsurface and an irregular decrease in organic C between 25 - 125 cm. Strongly contrasting particle size classes and prominent color change between adjacent horizons are evident at 83 cm. The convoluted bands with heavy minerals in the lower half of the profile are shown in Fig. 9.

Figure 7. Profile 9806-4 is Typic Udorthent as indicated by lack of pedogenic horizonation, or other distinguishing features in terms of soil classification.

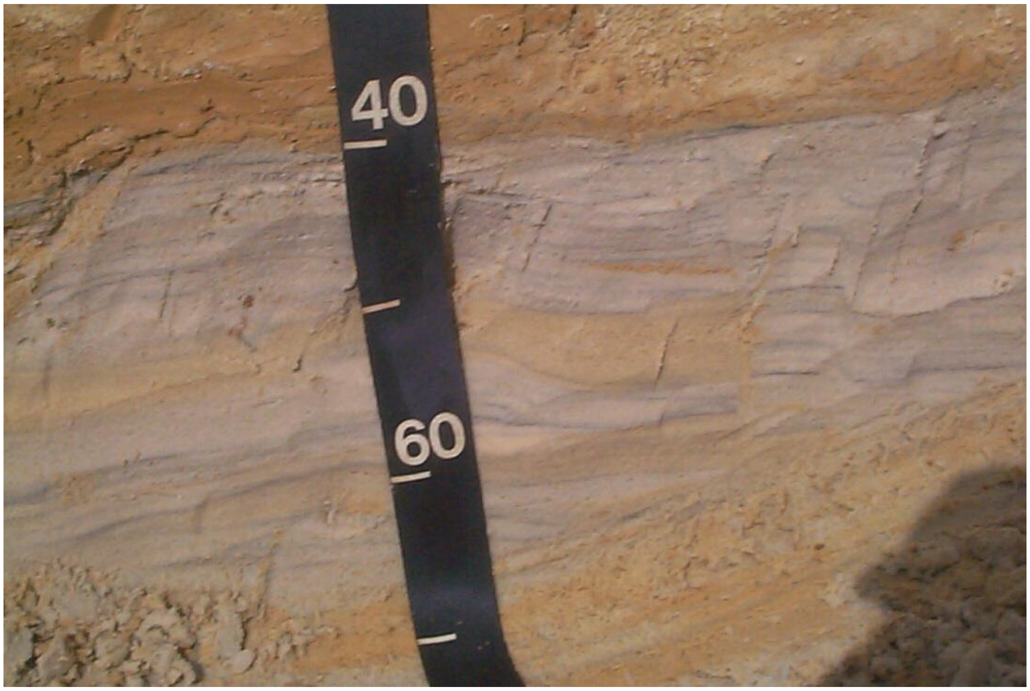

Figure 8. Alternating layers of tailing (lighter colored material) and slimes (redder material), with thin bands of black heavy minerals were evident in the subsurface (below 140 cm) of profile 9801-4.

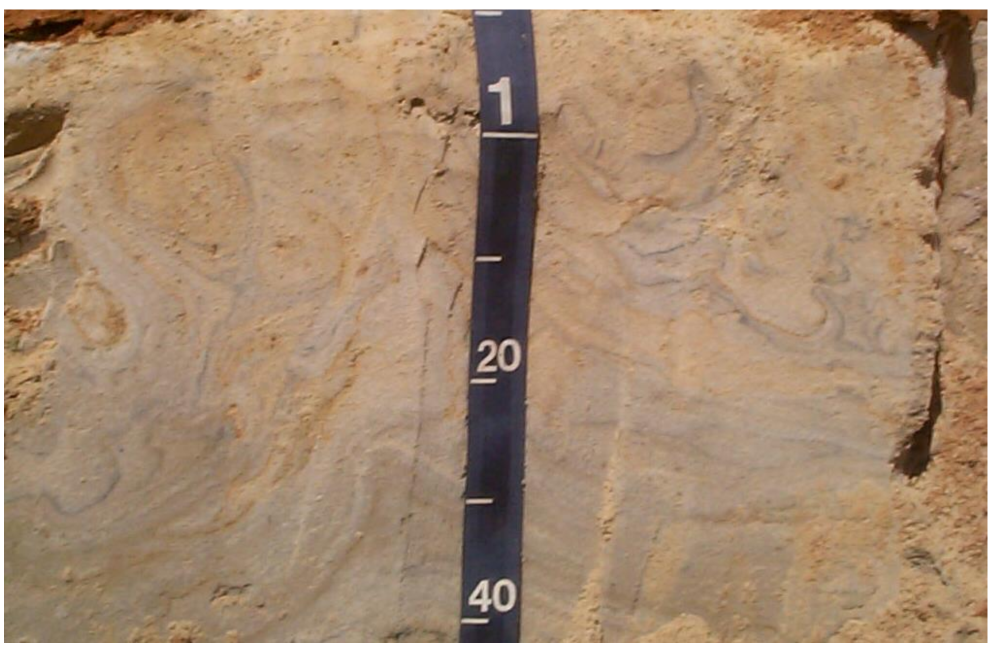

Figure 9. Thin bands of heavy minerals are overturned and deformed, referred to here as convoluted banding (Profile 9808-3).

Table 2. Profile descriptions of four representative mineral sands mine soils.

Horizon	Depth (cm)	Description
		<u>Profile 9801-1: Typic Quartzipsamment</u>
Ap	0 – 16	Yellowish brown (10 YR 5/6) sandy loam, with 5% bright reddish brown (5 YR 5/6) clay aggregates; weak medium subangular blocky structure; loose; common medium and fine roots; slightly alkaline (pH 7.5); abrupt smooth boundary.
C1	16 – 19	Bright yellowish brown (10 YR 6/8) sand; massive; loose; common medium roots; neutral (pH 6.9); abrupt smooth boundary.
C2	19 – 55	Light gray (10 YR 8/1) sand; massive; loose; distinct black heavy mineral bands; neutral (7.1); gradual smooth boundary.
C3	55 – 101	Dull yellow orange (10 YR 7/4) sand; massive; loose; 5% rock fragments (quartz pebbles and plinthite nodules); distinct black heavy mineral bands; slightly alkaline (pH 7.4); clear smooth boundary.
C4	101 – 125	Light yellowish brown (10 YR 6/4) sand; massive; loose; distinct black heavy mineral bands; neutral (pH 6.7); clear smooth boundary.
C5	125 – 200+	Brownish yellow (10 YR 6/6) sand; massive; loose; 10% rock fragments (quartz pebbles and plinthite nodules); strongly acid (pH 5.4).
		<u>Profile 9801-4: Fluventic Dystrudept</u>
Ap	0 - 17	Yellowish brown (10 YR 5/6) sandy clay loam; weak medium subangular blocky structure; friable; common fine and very fine roots; 1% rock fragments; moderately alkaline (pH 7.9); clear smooth boundary.
Bw	17 - 52	Dark yellowish brown (10 YR 4/6) sandy clay loam; moderate coarse subangular blocky structure; friable; common fine and very fine roots; 1% rock fragments; very strongly acid (pH 4.6); abrupt smooth boundary.
C1	52 – 97	Light yellowish brown (2.5 Y 6/4) sand; massive; very friable; 2% clay aggregates; very strongly acid (pH 5.0); clear smooth boundary.
C2	97 - 140	Yellowish brown (10 YR 5/6) clay loam, with 40% distinct bands of dull yellow (2.5 Y 6/4) sand; massive; friable; very strongly acid (pH 5.0); clear smooth boundary. Clear smooth boundary.
C3	140 – 200+	Dull yellow orange (10 YR 7/2) sand, with light yellow (2.5 Y 7/4) bands; massive; friable; strongly acid (pH 5.2).

Table 2, continued.

Horizon	Depth (cm)	Description
		Profile 9808-3: Typic Udifluvent
Ap	0 - 10	Strong brown (7.5 YR 5/8) sandy clay loam; weak coarse subangular blocky structure; very friable; many fine and very fine roots; 1% rock fragments (quartz pebbles); medium acid (pH 5.6); clear smooth boundary.
C1	10 - 38	Yellowish brown (10 YR 5/6) loamy sand; massive; very friable; common fine and very fine roots; 1% rock fragments; very strongly acid (pH 4.3); abrupt smooth boundary.
C2	38 - 51	Strong brown (7.5 YR 5/8) clay; massive; firm; very strongly acid (pH 5.0); clear smooth boundary.
C3	51 - 83	Yellowish red (5 YR 5/8) clay; massive; friable; very strongly acid (pH 5.0); abrupt smooth boundary.
C4	83 – 200+	Light yellow (5 Y 7/3) and dull yellow (2.5 Y 6/3) sand; massive; friable; distinct black heavy mineral bands; 5% distinct Fe concentrations between 110 to 130 cm; slightly acid (pH 6.2).
		Profile 9806-4
Ap	0 – 20	Olive brown (2.5 Y 4/3) sandy loam; weak fine subangular blocky over very thin platy structure; friable; medium fine and very fine roots; 10% Coastal Plain substratum materials; neutral (pH 7.2); gradual irregular boundary.
Cd	20 – 52	Brown (10 YR 4/6), grayish yellow (2.5 Y 6/2), and reddish brown (5 YR 4/6) sandy loam; weak very thin platy structure over massive; friable; few fine and very fine roots; 10% Coastal Plain substratum fragments and 1% rock fragments (quartz pebbles); very strongly acid (pH 4.8); gradual irregular boundary.
C1	52 – 77	Bright brown (7.5 YR 5/6) sandy clay loam; massive; firm; very few very fine roots; very strongly acid (pH 5.0); gradual irregular boundary.
C2	77 – 200+	Orange (7.5 YR 6/8) sand; massive; very friable; very strongly acid (pH 4.7).

Table 3. Some physical and chemical properties of representative mineral sands mine soils.

Horizon	Thickness	sand	silt	clay	OM	OC	pH	Ca	Mg	K	H	Al	CEC	ECEC	BS	EBS
	cm	--------------------- % ---------------------						-------------------- ug/ml --------------------					----- $cmol_c$/kg -----		------- % -------	
9801-1																
Ap	16	65.7	14.7	19.6	1.32	0.78	7.52	9.00	0.31	0.21	0.40	0.00	9.92	9.52	0.96	1.00
C1	3	97.2	2.3	0.5	0.09	0.04	6.94	0.33	0.05	0.02	0.00	0.00	0.40	0.40	1.00	1.00
C2	36	97.7	2.2	0.1	0.00	0.02	7.11	0.14	0.02	0.01	1.60	0.00	1.78	0.18	0.10	1.00
C3	46	98.7	0.4	0.9	0.00	0.02	7.44	0.16	0.02	0.01	0.00	0.00	0.19	0.19	1.00	1.00
C4	24	96.9	1.7	1.4	0.02	0.02	6.69	0.18	0.03	0.03	0.00	0.00	0.24	0.24	1.00	1.00
C5	75	96.8	2.6	0.6	0.00	0.02	5.44	0.13	0.02	0.02	0.40	0.00	0.57	0.17	0.29	1.00
9801-4																
Ap	17	61.9	12.5	25.5	1.25	0.95	7.91	15.78	0.57	0.33	0.00	0.00	16.68	16.68	1.00	1.00
Bw	35	51.6	18.3	30.1	0.27	0.18	4.61	1.87	0.70	0.09	5.00	2.30	7.66	4.96	0.35	0.54
C1	45	96.5	1.3	2.2	0.00	0.02	5.04	0.12	0.05	0.05	0.80	0.20	1.01	0.41	0.21	0.51
C2	43	57.2	16.7	26.2	0.16	0.17	4.98	1.26	0.52	0.15	6.40	2.60	8.34	4.54	0.23	0.43
C3	60	97.3	1.1	1.6	0.00	0.02	5.19	0.07	0.03	0.02	0.60	0.00	0.72	0.12	0.16	1.00
9808-3																
Ap	10	70.2	6.4	23.4	0.19	0.17	5.60	1.64	0.59	0.46	1.60	0.20	4.28	2.88	0.63	0.93
C1	28	87.0	3.1	9.9	0.00	0.07	4.33	0.56	0.25	0.06	1.00	0.60	1.87	1.47	0.47	0.59
C2	13	15.3	22.9	61.8	0.29	0.27	4.99	2.48	1.01	0.30	7.20	3.30	10.98	7.08	0.34	0.53
C3	32	8.2	25.4	66.4	0.30	0.27	4.97	2.29	0.85	0.27	10.00	3.00	13.41	6.41	0.25	0.53
C4	117	97.1	2.1	0.8	0.02	0.04	6.19	0.14	0.03	0.01	1.00	0.10	1.19	0.29	0.16	0.65
9806-4																
Ap	20	76.8	14.5	8.7	0.89	0.48	7.20	3.51	0.32	0.07	3.20	0.00	7.10	3.90	0.55	1.00
Cd	32	75.1	9.3	15.6	0.32	0.15	4.81	1.43	0.42	0.04	5.20	0.80	7.09	2.69	0.27	0.70
C1	25	53.1	13.7	33.2	0.46	0.21	4.98	1.32	0.67	0.17	8.80	2.10	10.95	4.25	0.20	0.51
C2	123	91.1	4.3	4.5	0.22	0.05	4.74	0.28	0.13	0.04	3.40	2.50	3.85	2.95	0.12	0.15

Surface Horizons

Only one pit, 9808, had not received biosolids prior to this study. This was evident in the color and depth of the plow layers as the three pedons from pit 9808 had a slightly redder surface hue (7.5YR) than that dominantly seen in the other profiles (10YR). Overall, soil colors varied only slightly ranging from strong brown (7.5YR4/6) to yellowish brown (10YR5/6) to olive brown (2.5Y4/3). The plow layers ranged from 10 to 24 cm in depth with an average thickness of 15 cm. The three pedons from pit 9808 had depths ≤ 13 cm. All of the surface soils consisted of friable loamy sands, sandy loams, and sandy clay loams with weak to moderate subangular blocky structure. Only one profile was distinctly different, which was a yellowish red clay with weak moderate angular blocky structure and a firm consistence. Seven profiles exhibited platy structure at the base of, or directly below, the Ap horizon as a result of surface compaction (discussed below). Five Ap horizons contained up to 10% fragments of Coastal Plain substratum materials and/or slimes. All of the sampled mining pits were vegetated with a mixed grass cover, and plant roots were well established throughout all of the surface soils.

The surface soils were dominantly neutral to mildly alkaline, with values ranging 5.6 to 8.0. Organic matter levels varied from 0.2 to 1.5% with an average of 0.9%. Cation exchange capacity (CEC) fluctuated with OM, with values ranging from 4.3 to 16.7 $cmol_c/kg$, and an average of 10.3 $cmol_c/kg$. Base saturation ranged from 54 to 100%. Pit 9808, the only pit that did not receive biosolids, had the lowest pH, OM and CEC values.

Subsurface Horizons

Three main components made up the subsurface of these profiles – sandy tailings, clayey slimes, and Coastal Plain substratum material. Consequently, the subsurface horizons were more highly variable in chemical, physical and morphological characteristics than the surface soils. However, a few related characteristics were common to all of the profiles. First, with few exceptions, the subsurface horizons were structureless. Most horizons were massive, particularly those with finer textured materials, although a few of the sandy layers were single grained. Second, the upper subsurfaces were dense, with seven profiles containing densic layers. Compacted zones were identified by being very firm in place, and by restricted rooting. The seven soils with densic layers also had platy structure at the base of the Ap, and three profiles exhibited oxidized rhizospheres, which further indicated compaction and associated impeded aeration. Compaction in the upper part of these soils resulted from the weight of heavy equipment during final grading, although to some extent compaction may have occurred lower in the profile from wet settling of the tailings and slimes. Finally, as mentioned above, root growth was limited due to compaction in combination with the massive, structureless nature of these soils. Rooting was limited to the upper 80 cm of most profiles, and on average to less than 45 cm. In a few profiles roots extended deeper (up to 97 cm), but only along vertical cracks in the soil.

Six characteristics were commonly observed in the subsurfaces. These features are artifacts of the depositional process, which resulted in the segregation of slimes and tails, as well as subsequent manipulation of the soil materials. Each of the thirteen pedons exhibited at least one of the following properties as indicated in Table 4:

1) One or more occurrences of strongly contrasting particle-size classes between subsurface horizons (Figs 5 and 6).

2) Significant color changes that were sometimes, but not always, in combination with textural changes (Figs 4 - 6).

3) Thin bands of tailing and slimes (Fig 5).

4) Thin bands of heavy minerals (Fig 6).

5) Bands of tailing, slimes, and/or heavy minerals that were overturned or deformed - referred to here as "convoluted banding" (Fig 3). Banding of this nature does not occur in natural soils that have not undergone cryoturbation, and may prove to be a diagnostic feature of these mine soils.

6) Fragments of clayey materials such as slimes or Coastal Plain substratum within a sandier matrix (Fig. 7).

The most uniform subsurfaces were seen in the three Quartzipsamments and one of the Udorthents (9801-2). Quartzipsamments are soils with no pedogenic horizon development that have sandy subsurface horizons, without excessive rock fragments, to a depth of at least 100 cm. The Udorthent would have classified as a Quartzipsamment had it not been for the presence of a horizon with 50% pebbles in the upper part of the subsurface. Three of these profiles were in mining pit 9801, which was backfilled dominantly with sandy tailings. The fourth was from mining pit 9806. This pedon was located near a slurry discharge point, which accounts for the sand accumulation in that corner of the field. All four profiles consisted of almost pure sand throughout the subsurface with colors that varied slightly among light grays, yellows and browns; however, pit 9801-3 deviated with an abrupt textural change to loam-textured slimes at 135 cm. In addition to the coarse layer mentioned above, several horizons contained small amounts (up to 10%) of quartz pebbles and hardened plinthite nodules. These soils had the shallowest rooting with depths of 35 to 45 cm. Of all the profiles, these four were the least acidic being only slightly acid to mildly alkaline. These near-neutral pH values are likely due to deep neutralization from repeated lime and lime stabilized biosolids applications. With virtually no clay to provide buffering, leaching effects were relatively deep (up to 2 m). The high sand content of these soils, in combination with only trace amounts of OM, resulted in very low CEC values throughout the subsurface.

Only one pedon (9801-4) exhibited a true pedogenically-developed subsoil horizon, described as Bw, which was indicated by the development of moderate subangular blocky structure in the sandy clay loam-textured bulldozed capping. This structural development allowed for slightly deeper rooting, with roots extending to 55 cm. Below the Bw, rooting was restricted by a dense, massive sand layer similar to those in the Quartzipsamments. This soil was strongly to very strongly acid throughout the subsurface, while OM (0 to 0.3%) and CEC (0.7 to 8.3 $cmol_c/kg$) fluctuated with clay content. The Bw horizon met all criteria, including thickness, texture, structure, and color requirements, for a cambic horizon. Consequently this was the only pedon to be classified as an Inceptisol (Fluventic Dystrudept), indicating the beginning of pedogenic profile development.

The eight remaining pedons were classified in other classes of Entisols since they did not exhibit natural pedogenic horizonation in the subsurface. Two profiles were classified as Typic Udifluvents due to an irregular decrease of organic C through the subsurface horizons. For pedon TP1-1, the deviation resulted from the presence of an A horizon (called Ab) which was

Table 4. Some physical and morphological characteristics common to mineral sands mine soils (x indicates presence of characteristic).

Profile	Ap texture	Depth of densic layers (cm) †	Banded materials	Convoluted banding	Heavy mineral banding	Dissimilar materials	Color change between adjacent horizons ‡	Contrasting particle-size classes †
9801-4	fine-loamy		x			x	distinct	x
9808-3	fine-loamy			x	x		prominent	x
TP1-1	coarse- loamy	45 - 86	x	x	x	x	distinct	x
9801-1	fine-loamy				x		prominent	
9801-3	coarse- loamy		x		x		prominent	x
9806-1	clayey			x			prominent	
9801-2	coarse- loamy			x			distinct	
9808-1	coarse- loamy	13 - 35	x			x	prominent	x
9806-2	coarse- loamy	12 - 36	x			x	prominent	x
9806-3	coarse- loamy	12 - 45	x	x		x	faint	x
9806-4	coarse- loamy	20 - 52				x	distinct	x
9808-2	fine-loamy	11 - 92					prominent	x
TP1-2	fine-loamy	16 - 70					prominent	xx

† as defined by Keys to Soil Taxonomy (Soil survey staff, 2003).
‡ as defined by NRCS Soil Survey Technical Notes, 2002

buried by additional capping material when the surface of this field was regraded. This soil was mildly alkaline through the Ab (to 45 cm), presumably due to documented liming before final reconstruction of the surface. The rest of the subsurface was strongly to very strongly acid. Similarly, OM and CEC values were relatively high through the upper half of the profile, and then decreased below the Ab. For profile 9808-3, the C increase was associated with two clay horizons containing low levels of OM (0.3%) in an otherwise sandy subsurface. Due to the combination of OM and high clay content, the clay layers had relatively high CEC values (11 to 13 $cmol_c$/kg), whereas CEC was negligible in the other subsurface horizons. The upper subsurface and the clay layers were very strongly acid, with an abrupt change to a slightly acid almost pure sand horizon similar to those seen in the Quartzipsamments.

The last 6 pedons were classified as Typic Udorthents. The following discussion refers only to these remaining profiles and not pit 9801-2, which was previously described. Four profiles (9806-4, 9808-1, 9808-2, and TP1-2) exhibited an irregular decrease in C levels such as those described above, but they were excluded from Fluvents due to the presence of shallow densic horizons (Soil Survey Staff, 2003). Densic layers were observed in all 6 of these Udorthents. The presence of shallow densic materials affects the extent of the particle-size control section which may profoundly affect family level classification. Four profiles had horizons containing fragments of Coastal Plain substratum within a sandy matrix. These soils could qualify as Arents if the fragments proved to be part of a dignostic cambic or argillic horizon, but more rigorous evaluation of the material would be necessary to justify that classification. The other two profiles also contained horizons with dissimilar materials, but this was indicated by color variegation rather than textural differences. All six subsurfaces were very strongly to medium acid, with pH values ranging from 4.6 to 5.7. Organic matter was typically low in the subsurfaces, although slightly higher values (up to 0.5%) were associated with finer-textured horizons and a buried A horizon (1.3%). Similarly, CEC values were relatively low, and increased with increasing clay and OM up to 14 $cmol_c$/kg.

Conclusions

Evaluation of thirteen pedons from four reclaimed mining pits revealed four different soil subgroups. These subgroups included, in order of prevalence, Typic Udorthents, Typic Quartzipsamments, Typic Udifluvents and Fluventic Dystrudepts. One pedon exhibited a pedogenically altered subsoil horizon (Bw), and two had buried Ab horizons. The other pedons all exhibited simple A-C horizonation. The Ap horizons varied slightly in terms of color, texture and structure. Greater differences were seen in chemical properties, which was in part due to the addition of lime stabilized biosolids. The pedons from pit 9808, the only pit that did not receive biosolids, were thinner with lower pH, OM and CEC values than the other pits. Subsurface materials, which consisted primarily of tailings, slimes and fragments of Coastal Plain substratum, were highly variable among and within the profiles. Overall, the subsurfaces tended to be acidic ($pH \leq 5.5$) with low OM and CEC; however, finer-textured horizons were commonly associated with slightly higher OM and CEC. Soils that were sandy throughout the subsurface were less acidic due to deep neutralization from surface amendments. Six morphological characteristics were commonly observed in these profiles, including: i) abrupt textural changes between adjacent horizons, ii) abrupt color changes between adjacent horizons, iii) banding of tails and slimes within a horizon, iv) heavy mineral banding, v) convoluted banding, and vi) presence of dissimilar materials (other than banding) within a horizon. For all pedons, high subsurface densities coupled with weak structural development restricted rooting and will pose major long-term limitations for returning these soils to pre-mining productivity levels. Abrupt textural changes between adjacent horizons, which were seen in several profiles, will also hinder agricultural use of these soils by impeding drainage. Until new procedures are developed to effectively flocculate and co-mingle the slimes fraction with the sandy tailings as they are dewatered, strong lateral and vertical variability of mine soil texture and associated chemical conditions will be the expected condition, and will strongly differentiate revegetation success across reclaimed mining pits.

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