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AN APPLICATION OF THE RUNGE "ENERGY MODEL" OF SOIL DEVELOPMENT IN MICHIGAN'S UPPER PENINSULA

Randall J. Schaetzl[1] and Charles Schwenner[2]

This paper examines some soils in Michigan's upper peninsula that do not "fit" with the zonal soils of the region. The typical upland soils in this part of the Pictured Rocks National Lakeshore (PRNL), when not constrained by bedrock or high water tables, are strongly developed Spodosols (Haplorthods). We used the energy model (Runge, 1973) as a conceptual guide to help explain the genesis of nearby soils, whose chemistry and morphology are very different. The energy model presupposes that soils are affected mainly by water available for leaching and organic matter production, as conditioned by parent material. In our study area, where water available for leaching is limited (or even negative), as on steep slopes shallow to bedrock with multiple springs and seeps, and where erosional processes are strong, horizonation in the classical sense does not form. Instead, shallow Histosols (Saprists) form above bedrock, even on 45% slopes. Oxyaquic Haplorthods developed on flat uplands, on the same bedrock, are strongly horizonated, as most of the water that impacts them is available for leaching and pedogenesis. In another example, soils that have formed above calcareous bedrock maintain such high pH values that their faunal assemblages are rich and diverse, and base cycling is strong, leading to thick O + A horizon sequences. These soils (Lithic Udipsamments) resemble Mollisols and exhibit few marks of podzolization. Conversely, nearby Oxyaquic Haplorthods above acid sandstone bedrock have limited faunal assemblages, slow organic matter decomposition, and horizonation indicative of strong podzolization. These examples highlight how conceptual models can be used to guide our understanding of soil genesis and distribution. (Soil Science 2006;171:152–166)

Key words: Pedogenesis, conceptual models, podzolization, base cycling, bedrock influence.

SOILS are extremely complex natural phenomena. Only by using conceptual models can we better understand and explain the complexity of the pedogenic system and distinguish signal from noise. Rather than being precise mathematical formulations that can be solved, conceptual pedogenic models help put soils information into perspective and provide insight into the system interrelationships, process linkages, and the nuances of pedogenesis (Dijkerman, 1974; Johnson and Watson-Stegner, 1987; Smeck et al., 1983). They take the complex and make it simple; they are simplified descriptions of natural systems.

History is full of examples by which the application of certain pedogenic models has influenced perceptions of soil genesis. It is equally full of examples in which models have been largely ignored. In the latter situation, had these models been used, the way in which the natural systems were perceived might have been very different.

One pedogenic model that has perhaps received less than its due amount of distinction is the "energy model", developed by Ed Runge, a soil scientist then at the University of Illinois

[1]Department of Geography, 314 Natural Science Building, Michigan State University, East Lansing, MI 48824-1115. Dr. Randall J. Schaetzl is corresponding author. E-mail: soils@msu.edu

[2]USDA-Natural Resources Conservation Service, 201 Rublein Street, Marquette, MI 49855.

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(Runge, 1973). Despite its potential as a hybrid pedogenic model, the energy model has received little fanfare and has been applied only selectively. Although frequently included in theoretical reviews, for example, Barrett (1999), Dijkerman (1974), Hoosbeek and Bryant (1992), Huggett (1975), Johnson (2000), Phillips (1989), Smeck et al. (1983), and Yaalon (1975), given its status as a major pedogenic model, its use/citation in empirical soils research has been limited to a very few papers, all of which essentially mention the model but do not directly use it in their research design, for example, Cremeens and Mokma (1986), Honeycutt et al. (1990), Rockwell and Loughman (1990), and Singleton and Lavkulich (1987). Only Brye's (2004) paper expressly uses the model to explain soil patterns and development.

Our research in a complex, bedrock-controlled landscape in Pictured Rocks National Lakeshore (PRNL), in Michigan's (USA) upper peninsula, uses the Runge model to help understand the genesis of the soils therein. In applying the model, we not only provide an example of its utility but also test its applicability and robustness outside of the range of conditions in which it was developed. Our application of the energy model may actually heighten its appeal and open up new avenues for its applicability within the pedologic and soil geomorphic communities.

THEORETICAL BACKGROUND

Runge's energy model uses pieces of two preexisting conceptual models: Jenny's (1941) functional–factorial model and Simonson's (1959) process systems model. Jenny's model formulates soil as being a function of five state factors (Stephens, 1947). State factors resonate with many soils scholars and mappers, and like many "successful" models, Jenny "sold" it well by writing about it clearly. Each state factor is meant to define the state and history of the soil system (Wilding, 1994). They are not forces or causes but rather factors—independent variables that define the soil system. This functional–factorial model is expressed as

$$S = f(cl, o, r, p, t, \ldots), \quad (1)$$

where S is the soil or a soil property, cl is the climate factor, o is the organisms factor, r is the relief factor, p is the parent material factor, t is the time factor, and the string of dots represents other, unspecified factors that may be important locally but not universally, such as inputs of eolian dust, sulfate deposition in acid rain, or fire. The factors define the soil-environmental system in terms of the controls on pedogenesis (Scull et al., 2003; Wilding, 1994). To precisely define the state of the soil system, as the model attempts to do, we need to address and define at least five aspects of it—its five state factors. The factors were not meant to explain how these particular conditions influenced soil properties, that is, if this was not a *process model*, only that a given set of environmental conditions would result in the formation of a particular soil property. In the state factor model, climate and organisms are considered to be "active" factors whereas relief, parent material, and time are more "passive", that is, they are being "acted upon" by active factors and pedogenic processes. The parent material factor reflects the initial state of the system. The functional–factorial model remains the standard against which all other pedogenic models are still judged—the main model used to explain soil distributions at most scales.

On the other end, so to speak, of the model continuum is the process-based model of Roy Simonson, developed and presented in his 1959 paper, and later refined (Simonson, 1978). Unlike the state factor model, which focused on factors that affected pedogenesis but said nothing directly about pedogenic processes, Simonson's model was entirely process based. He observed that soils all have similarities and differences, and that their differences are due to the varying strengths of the same types of *pedogenic processes*, operating on similar materials. In the process systems model, pedogenesis is viewed as consisting of two steps: (1) the accumulation of parent material and (2) the differentiation of that parent material into horizons; Simonson's model focuses on the second step. He felt that soils differed because the processes they shared varied in degree, not kind. The four major kinds, or bundles, of processes were designed, by necessity, to be very general to cover the entire range of pedogenic processes (Smeck et al., 1983). Although not originally conceived as an equation, the model can be written as

$$S = f(a, r, t_1, t_2), \quad (2)$$

where S is the soil, a is additions, r is removals or losses, t_1 is transfers/translocations, and t_2 is transformations. Simonson envisioned that losses and additions are to the soil (pedon) as a whole, whereas translocations occur between horizons within a single pedon. These four sets of processes occur simultaneously in all soils; their balance and character govern the nature of the soil (Simonson, 1978).

The process systems model was not developed for, and has not found strong usage in, the interpretation of soil spatial variability; for this purpose, the functional–factorial model (Jenny, 1941) is more appropriate. Users of Simonson's model have to have some knowledge of processes to effectively apply it to explain soil spatial variability.

Runge's (1973) model merges the strong process formulation of the Simonson model into Jenny's factorial framework. Runge emphasized two *priority factors* from Jenny's model, climate and relief. He combined them into a single *intensity factor* that he defined as the amount of *water available for leaching* (w), which was governed by climate and topography, via precipitation and runon/runoff. Thus, the two factors combine to form a process vector that is roughly comparable to the potential for water to infiltrate and percolate through, that is, leach, through the profile. Runge saw the w factor as an organizing vector that utilized gravitational energy to move water through the profile, organize the profile, decrease profile entropy and form horizons, that is, make it more anisotropic and horizonated. Water that runs off the surface, that is not available for leaching, represents gravitational energy that is lost to the system.

Runge also combined parent material and organisms (assuming that the o factor was primarily concerned with flora) into a single *intensity factor* called *organic matter production* (o), or lack of mineralization. The rationale for the o factor is somewhat indirect and complex. Because plants are the main source of soil organic matter (SOM), Runge assumed that their ability to grow and produce SOM was governed largely by parent material. For example, in infertile parent material, little organic matter can be produced. Thus, although a number of environmental factors govern the amount of SOM production, Runge felt that many of them were captured by the parent material factor. Unlike water available for leaching (w), however, the o factor was seen as a renewing or rejuvenating vector. For example, as SOM coats mineral soil particles via melanization, it inhibits weathering. The prairie grasses near Runge's Illinois home are also excellent base cyclers, and thus the more fertile the parent material, the better these grasses grow and the more bases that can be cycled, thereby maintaining a high soil pH and inhibiting processes like weathering and acidification. These examples illustrate the point that the more humus-rich the profile, the less weathered and the more isotropic (less developed) it might be (Schaetzl, 1991). Consequently, Runge viewed parent material and biota as working in unison, as an o factor that offset the w factor. Both intensity factors operate over time (t), as in Jenny's (1941) model.

Runge's model relies heavily on gravitational energy that drives infiltrating water and in turn causes horizonation, as well as (indirectly) on radiant solar energy for organic matter production. Thus, it has come to be known as the energy model (Smeck et al., 1983):

$$S = f(o, w, t), \qquad (3)$$

where S is the soil, o is organic matter production, w is water available for leaching, and t is time. Each of the two intensity factors (w and o) is conditioned by a number of capacity factors. For example, w is conditioned by duration and intensity of rainfall, runoff vs. runon, soil permeability, and evapotranspirative demand, whereas o is conditioned by nutrient (especially P), air and water availability, soil fertility, available seed sources, and fire.

The energy model combines many of the positive attributes of factor-based and process-based models; it is simple, easily comprehended, and process oriented. Applicable in a number of settings where sites with excess water due to runon tend to have more strongly developed and horizonated soils, it works best in strongly leaching environments (Schaetzl, 1990). (Runge noted that it is probably limited in application to soils on unconsolidated, permeable deposits like loess or till.) For example, on the prairies of Saskatchewan, Miller et al. (1985) reported on "depression-focused" recharge by snowmelt that leads to greater leaching in those areas. Sola were thicker in these sites, where water available for leaching was greatest, (Pennock et al., 1987). In areas where a high water table limits water available for leaching, soil development is also inhibited, further illustrating the efficacy of the model. These and similar studies, for example, Anderson and Burt (1978), Donald et al. (1993), and Manning et al. (2001), continue to find that infiltrating and percolating water are a source of organizational pedogenic energy and in so doing validate the model. And yet despite its potential applicability in the explanation of soil spatial variability, the model is seldom directly utilized in empirical, pedogenic research.

The energy model is not without shortcomings (Schaetzl and Anderson, 2004). One criticism of the model centers on the *o* factor. In Runge's Eastern Illinois surroundings, soils are mostly Mollisols in which humic-acid-rich, high pH organic matter retards weathering and inhibits horizon differentiation. However, in forested regions, especially forests with a coniferous component, organic matter is acidic and via the chelating action of fulvic acids formed by their decomposition, horizonation is promoted. Even in such landscapes, however, the model has utility; Schaetzl (1990) reported on accelerated soil development in pits formed by tree uprooting due to increased infiltration there. Pits also have higher organic matter contents but in the forests of Michigan the acidic SOM acts as an organizing vector.

STUDY AREA

Our study was conducted in the bedrock-controlled uplands of PRNL in Michigan's upper peninsula, near Lake Superior (Fig. 1), where thin glacial drift overlies Cambrian bedrock (Haddox and Dott, 1990; Hamblin, 1958, 1961; Reed and Daniels, 1987). The lowest rock unit in the study area is the quartz sandstone-dominated Munising Formation, which has two sandstone members: the acid, Chapel Rock and the overlying, more resistant, acid Miner's Castle. The white or buff-colored Chapel Rock sandstone is a well-sorted, medium-grained sandstone that attains a thickness of 12–18 m (Hamblin, 1958). It is extremely "clean", composed almost entirely of quartz, chert, and quartzite grains, with only minor amounts of feldspar (Hamblin, 1958). Silica is the dominant cementing material. Zircon and tourmaline are well represented in the heavy mineral fraction (Hamblin, 1958). The Miner's Castle sandstone is also extremely quartz-rich but is less sorted that the Chapel Rock.

Overlying these sandstones is the light brown to white Trempeleau (*aka* Au Train) Formation, which consists of interbedded, medium-grained to fine-grained, dolomitic sandstones and sandy dolomites, with many lenses of sandstone (Dorr and Eschmann, 1970; Hamblin, 1958). The Trempeleau Formation is the most resistant bedrock in the region and forms the caprock for several waterfalls. Thus, the local bedrock sequence is one that begins with acidic sandstones and develops increasing dominance by calcareous materials upward in the stratigraphic column and southward in the region (Fig. 1). Each of the bedrock units dips gently to the south, toward the center of the Michigan structural basin (Blewett, 1994).

The bedrock is mantled by sandy glacial drift (Albert, 1995; Blewett, 1994). In many places near the study area, the drift is less than a few meters meter thick on uplands; local topography is strongly impacted by bedrock. The area was last glaciated by the Marquette advance, a short readvance whose proglacial sediments buried a forest near Marquette at approximately 10,000 radiocarbon years B.P. (Clayton and Moran, 1982; Lowell et al., 1999). Most landforms in the study area had probably formed by 9300 years B.P. (Blewett, 1994).

The soils in Northern Michigan, by virtue of their coarse textures, cool snowy climate, and mixed coniferous deciduous vegetation, are influenced by podzolization (Barrett, 2001; Messenger et al., 1972). Podzolization is especially strong in this region (Schaetzl and Isard, 1996), leading to the formation of soils with some variant on O-A-E-Bhs-Bs-BC-C horizonation. Carbonates in the parent material must be weathered and leached from the pedogenic system before podzolization can proceed—a precondition that occurs rapidly in these strongly leached, coarse-textured soils.

MATERIALS AND METHODS

Sites and Site Selection Criteria

Maps and preliminary fieldwork had indicated that upland soils in the study area are shallow to calcareous bedrock and have morphologies that are not typical of Typic and Entic Haplorthods that have formed in deep sandy drift nearby. Using reconnaissance soil maps, we surveyed the landscape to locate the map units that might contain soils whose morphology/genesis seemed atypical for the region. We hypothesized that the morphology of the shallow-to-bedrock soils may be largely due to their bedrock influence.

We sampled nine pedons in the PRNL study area; site selection was guided by reconnaissance soil maps provided by the Alger County Soil Survey of the USDA-NRCS (of

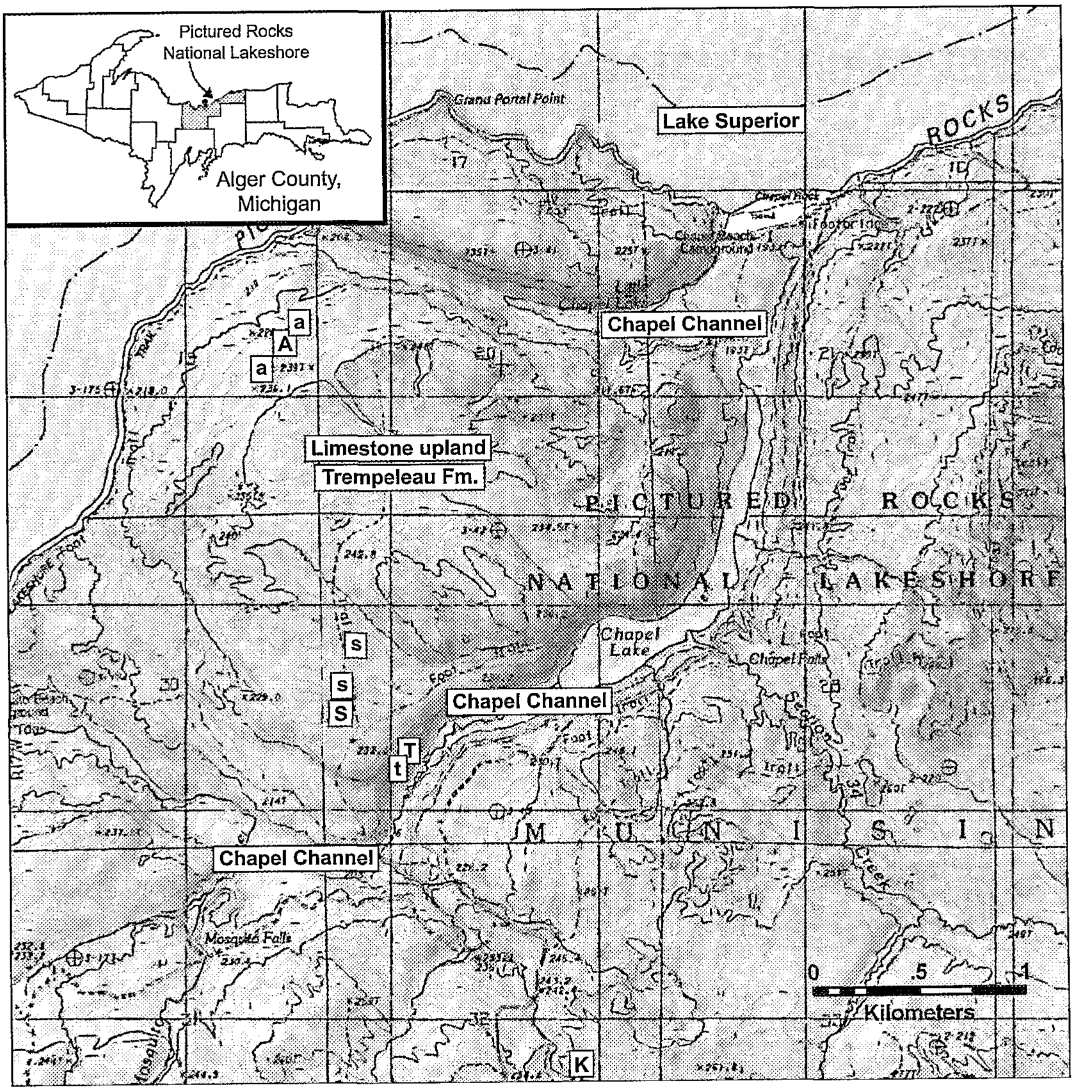

Fig. 1. Study area map on a USGS topographic map base (USGS Grand Portal Point Quadrangle, 1:25,000, 1983). Local topography and the locations of the pedons that are the focus of this research are indicated. K, Kalkaska; S, Shingleton; A, Au Train; T, Trout Bay. Sites identified with lowercase letters represent sites that were excavated and sampled but not discussed in detail herein.

which Schwenner is the survey leader). All sites are located on or near a high bedrock plateau surrounded by a low valley, carved by glacial meltwater, known locally as the Chapel Channel (Fig. 1). Topography here is mainly due to the resistance of the Trempeleau Formation, which underlies the bedrock upland, and incision into the softer sandstones below by glacial meltwater (Blewett, 1994). Groundwater continually seeps out of the Munising Formation sandstones where they are exposed on the sides of the meltwater channels.

Our initial pedon—a control pedon of sorts—was chosen for study because it is typical of soils forming in deep, acid sands—a sandy, mixed, frigid, Typic Haplorthod. This soil, the Michigan state soil (Kalkaska sand), is widespread in the area, where bedrock (parent material) control and wetness are not overriding pedogenic factors and where the parent material is sandy. At this site (Fig. 1) the drift is so thick as to negate any influence of the underlying bedrock.

Three additional pedons were then sampled on the bedrock upland, where it is mantled by thin (generally <3 m thick) drift over the sandy dolomite of the Trempeleau Formation (Fig. 1). These pedons are were sampled within a map unit of Shingleton sand, 0–2% slopes: sandy, mixed, frigid Lithic Haplorthods. Shingleton soils do not display the typical A-E-Bs-C Spodosol horizonation; instead they have thick, dark A horizons. Some pedons within Shingleton map units have been sampled by NRCS personnel and classify as Hapludolls. Most also lack an E horizon, perhaps due to intense earthworm bioturbation. High pH values (6.0–7.5) within the sola attest to the presence of shallow, calcareous bedrock of the Trempeleau Formation. These pedons were sampled because they provide a test of how the *o* factor of the energy model might impact pedogenesis, particularly regarding base status of the parent material and base cycling.

Five additional pedons were sampled on and near the flanks of the Chapel Channel, which is shallow to sandstone. Three pedons are on the far northern edge of the study area, in a channel cut by meltwater into the acid Miner's Castle sandstone (Fig. 1), on the flat "tread" portion of a strath terrace within the Chapel Channel. They are mapped in the moderately well-drained Au Train series (sandy, mixed, frigid, shallow Oxyaquic Haplorthods). Within the context of this study, Au Train soils are viewed as having taken an alternative pedogenic pathway from that of Shingleton soils. Both series are strongly influenced by the nature of the bedrock below the thin drift cover. For both, the state factors are similar except for parent material; Au Train soils have formed above acid sandstone bedrock whereas the Shingleton pedons overlie calcareous bedrock. From the perspective of the energy model, therefore, the *o* factors (as regards base cycling characteristics) for these two series are almost antipodal.

The last two sampled pedons on the flanks of the Chapel Channel are on a steep (generally >30%), southeast-facing slope that is almost continually wet from water seeping out of the Miner's Castle sandstone (Fig. 1). The wet but steep slopes of the Chapel Channel contained lithic Histosols over a thin, sandy mantle on acid sandstone bedrock. The soils here are mapped. within a Trout Bay (euic, frigid Lithic Haplosaprists) map unit. Steep slopes are certainly not the "normal" environment of formation for organic soils. Although these soils classify within a poorly drained series, they nonetheless have little "water available for leaching" because of the shallow bedrock and the continued additions of water at the base of the solum (seeping from above). Thus, the Trout Bay soils were viewed as an example of the alternative pedogenic pathway—if the *w* factor in the energy model were to be drastically impacted, or essentially negated (Fig. 2).

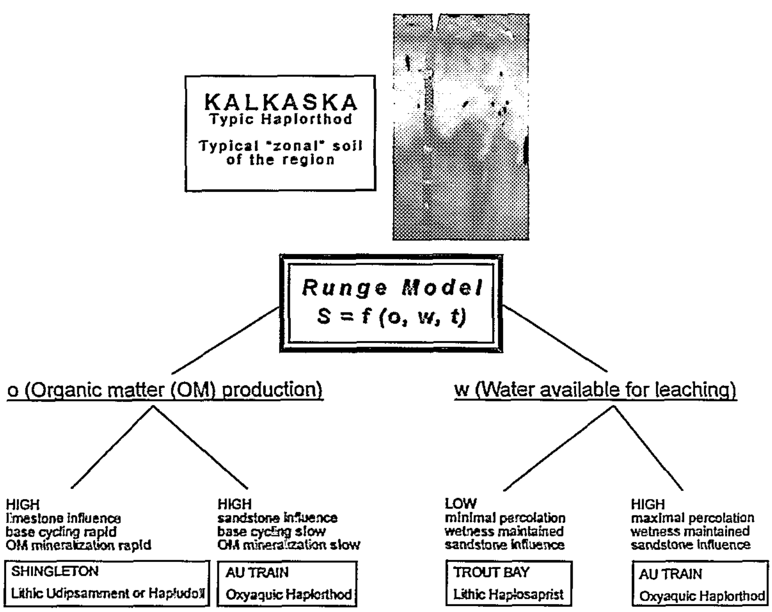

Fig. 2. The theoretical placement of each of the soils examined in this study, that is, how their development can be examined within the construct of the energy model.

Field and Laboratory Methods

At each site, a pit was opened by hand, to bedrock or the C horizon, whichever was deeper, and the soil profile described according to standard procedures (Soil Survey Division Staff, 1993). Samples of about 1 kg were taken from the profile face, for each genetic horizon, and air-dried. Where possible, we also sampled the bedrock. Coarse fragments (>2-mm diameter) were removed by sieving and discarded. Soil pH (2:1 soil/water on mineral samples, 8:1 on organic samples) was measured with a model #IQ150 handheld pH meter (Dual pH Technology, IQ Scientific Instruments); we report only the mean of two replicate pH analyses. Particle size analysis was performed by pipette (Soil Survey Laboratory Staff, 1996). Organic matter content was determined by loss on ignition (8 h at 430 °C) (Davies, 1974). Elemental composition of the fine earth fraction was determined by X-ray fluorescence. Samples were first ground to silt size. Three grams of this finely ground powder was then diluted by adding 9.0 g of lithium tetraborate ($Li_2B_4O_7$) and 0.5 g of ammonium nitrate (NH_4NO_3) as an oxidizer. This mixture was then melted in a platinum crucible at 1000 °C of oxidizing flame for >20 min while being stirred on an orbital mixing stage. The melt was poured into platinum molds to make glass disks, which were analyzed with an X-ray fluorescence spectrometer. XRF major element (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P, Rb, Sr, and Zr) analyses were reduced by a fundamental parameter data reduction method, whereas XRF trace element data were calculated using standard linear regression techniques.

Using the elemental data as surrogates for mineralogy, a soil weathering index was developed based on the assumption that, with time and increased weathering, elements derived from resistant, immobile minerals such as zircon (Zr) and anatase, rutile, and tourmaline (Ti) increase in abundance, relative to elements derived mainly from weatherable minerals, which are assumed to be pedogenically mobile (Ruhe, 1956; Santos et al., 1986). The weathering index was calculated by

$$\text{Weathering Index} = [(\text{Ti} + \text{Zr})/(\text{Ca} + \text{Mg} + \text{K} + \text{Mn} + \text{Na} + \text{P})] \times 100 \quad (4)$$

In addition, an index designed to reflect the degree to which soils have been podzolized and/or leached was calculated as

$$\text{Podzolization/Leaching index} = [(\text{Si} + \text{Ti} + \text{Zr})/(\text{Al} + \text{Fe})] \times 100 \quad (5)$$

Both of these indices are new to this study and have not been used in previous research.

Podzolization is expressed chemically as grain coatings in the B horizon, and lack of them in the E horizon. Therefore, we wanted to know the amounts of the various types of Fe and Al compounds that exist as grain coatings (McKeague, 1967; McKeague and Day, 1966; Parfitt and Childs, 1988). All mineral horizon samples were subjected to three extractants: sodium citrate-dithionite (CD), acidified ammonium-oxalate (AAO), and sodium pyrophosphate (PP) (Ross and Wang, 1993). CD primarily extracts "free" Fe and Al, denoted by Fe_d and Al_d, from pedogenic oxide minerals (Jackson et al., 1986). AAO extracts "active" Fe and Al (Fe_o and Al_o) from noncrystalline hydrous oxides. "Active" refers to oxides that are small in size and have a high surface area and degree of reactivity. PP extracts Fe and Al (Fe_p and Al_p) from organically bound complexes and, to a lesser degree, noncrystalline hydrous oxides. The supernatants were analyzed for Fe and Al on a Thermo Jarrell Ash 61E inductively coupled plasma spectrometer (U.S. Environmental Protection Agency, 1986).

RESULTS AND DISCUSSION

The Kalkaska "control" pedon typifies the well-developed, upland Spodosols of the Great Lakes region (Franzmeier and Whiteside, 1963; Schaetzl 2002), having formed in deep, coarse-textured, freely draining parent materials. The Kalkaska pedon exhibits typical O-A-E-Bhs-Bs-Bsm-BC-C horizonation and "sets the standard" for podzolization–leaching values for this suite of soils (Table 1, Fig. 3B). The energy model's utility comes to the fore when one attempts to explain the formation of the three *other* pedons, all of which are within 4 km of the Kalkaska soil but which differ markedly in morphology and pedo-chemistry.

Water Available for Leaching

At the Trout Bay site, our sampled pedon classified within that series, as a Lithic Haplosaprist. This soil illustrates how horizonation is impeded when percolation is restricted or minimized (Tables 1 and 2). From a theoretical perspective, Trout Bay soils, which have formed on the steep side slopes of the Chapel Channel (Fig. 1), are nearly constantly wet but have

TABLE 1

Physical and morphological data for the four most representative soils studied[†]

Horizon	Depth (cm)	Munsell color (moist)	Fragments >2-mm diameter (estimated volume %)	Sand (%)	Silt (%)	Clay (%)	Texture class[‡]	Structure (grade, size, shape)[§]	Consistence (moist, unless otherwise indicated)[§]
Kalkaska (site K on Fig. 1): An excessively drained Typic Haplorthod formed in deep sandy drift									
Oi	0–3	–	0	–	–	–	–	–	–
A	3–7	10YR 3/1	0	93.3	4.1	2.6	S	w f gr	v fr
E	7–52	5YR 5/2	0	97.6	0.6	1.9	S	structureless	v fr
Bhs	52–65	5YR 3/2 and 5YR 2.5/1	0	96.9	0.8	2.3	S	w f sbk	fr
Bs	65–104	5YR 3/3 and 10YR 4/6	0	98.3	0.1	1.6	S	w m&c sbk	fr/fi
Bsm	104–154	5YR 4/6 and 7.5YR 4/6	0	98.4	0.5	1.1	S	massive	fi/fr
BC	154–193	7.5YR 5/4	0	98.6	0.0	1.4	S	structureless	v fr
C1	193–221	10YR 5/4	0	99.1	0.8	0.1	S	structureless	v fr
C2	221+	10YR 4/4	0	98.2	0.0	1.8	CS	structureless	v fr
Au Train (site J on Fig. 1): A moderately well-drained Oxyaquic Haplorthod formed in sandstone residuum over sandstone bedrock									
Oi	0–3	–	0	–	–	–	–	–	–
Oa	3–15	2.5YR 2.5/0	0	–	–	–	–	w m gr	v fr
E	15–45	7.5YR 7/0	5	96.4	0.8	2.8	CS	structureless	l
Bhs1	45–58	5YR 2.5/2	5	95.1	2.1	2.8	CS	w f sbk	v fr
Bhs2	58–73	2.5YR 2.5/2	5	93.7	2.4	3.9	CS	w f sbk	fr
R	73+	7.5YR 5/8	–	94.4	2.8	2.8	CS	–	indurated sandstone
Shingleton variant (site S on Fig. 1): A well-drained Lithic Udipsamment formed in coarse-loamy materials over calcareous bedrock									
Oi	0–2	–	0	–	–	–	–	–	–
Oa	2–12	N 2/0	0	–	–	–	–	w vf gr	v fr
A	12–18	10YR 2/1	2	86.5	10.8	2.7	CS	w f&m sbk	v fr
BA	18–21	7.5YR 3/4	5	85.8	10.2	4.0	LCS	w f sbk	v fr
Bs	21–35	5YR 3/4	5	89.6	7.0	3.3	CS	w f sbk	v fr
2R	35+	–	–	–	–	–	–	–	indurated limestone
Trout Bay (site T on Fig. 1): A very poorly drained Lithic Haplosaprist formed in organic materials over sandstone bedrock									
Oa	0–16	N 2/0	0	–	–	–	–	m vf gr	sl stcky (wet)
A	16–30	N 2/0	0	88.3	7.3	4.4	CS	w m&c sbk	sl stcky (wet)
2Cr	30–33	–	0	94.2	2.6	3.3	CS	structureless	v fr
2R	33+	–	0	89.2	7.6	3.1	CS	indurated	indurated sandstone

[†]Although we sampled nine pedons (Fig. 1), they fall into four categories: a control pedon (Kalkaska), pedons on acid sandstone bedrock (Au Train), pedons on calcareous bedrock (Shingleton), and Histosol pedons on steep slopes (Trout Bay). With the exception of Kalkaska, we sampled at least two pedons in each category, but for brevity only one example of each is provided here.

[‡]S, sand; CS, coarse sand; LCS, loamy coarse sand. Textures according to the Soil Survey Division Staff (1993).

[§]Structure: Grade (w, weak; m, moderate); Size (vf, very fine; f, fine; m, medium; c, coarse); Shape (gr, granular; sbk, subangular blocky). Consistence: l, loose; v fr, very friable; fr, friable; fi, firm; sl sticky, slightly sticky.

minimal vertical percolation. Instead, intrapedon soil water flows parallel to the surface or rises up from below, exiting the soil at its surface, as seeps. The energy model predicts that soils with little water available for leaching will be minimally developed, and that is the case here (Fig. 2); Trout Bay soils are essentially accumulations of organic matter, in various stages of decay, above bedrock. And with the exception of the bedrock below the Shingleton pedon, the Trout Bay soil also has low weathering indices (Fig. 3A), again indicating minimal development (or erosion of weathered sediment as it accumulates). An additional factor that helps to explain the morphology of the Trout Bay pedon is the steep slope, which accentuates erosion and keeps the pedon's mineral horizons minimally developed and thin.

Starkly in contrast to the Trout Bay pedon is the Au Train (Tables 1 and 2), which is essentially a "flat upland version" of Trout Bay in that it has formed above sandstone, is acidic and deeply leached, and exhibits strongly contrasting horizonation. The Au Train site we sampled is mapped as an Oxyaquic Haplorthod and also classified as such (Table 1). Long-term development and leaching of cations (downward as well as laterally, above the bedrock contact) has lowered the pH in the Au Train soil to the 4.1–4.8 range, whereas in the Trout Bay soil most horizons are near neutrality (Table 2). The Au Train soil has the most pronounced eluvial–illuvial sequum of all the soils in the region; its bright white (7.5YR 7/0) E horizon has been nearly completely eluviated of silt, clay, iron, and aluminum, whereas the dark brown and in places nearly cemented B horizon (which rests on shallow saprolite) retains large concentrations of the same illuvial materials. The Au Train pedon has, by far, the highest podzolization/leaching index of all four soils in this study (Fig. 3B). The boundary between the Bhs and R horizons is gradual (some saprolite does exist), reflecting the ongoing bedrock weathering processes that thicken the profile; these processes are nearly absent in Trout Bay soil, which has a very thin saprolitic horizon. In summary, these two soils illustrate the importance of percolating water, that is, water available for leaching, to the soil system. This distinction is captured nicely by the energy model as the *w* factor.

Organic Matter Production (and Base Cycling)

In many soils in dry environments, organic matter decomposition is inhibited by base cations, particularly Ca (Duchaufour, 1976;

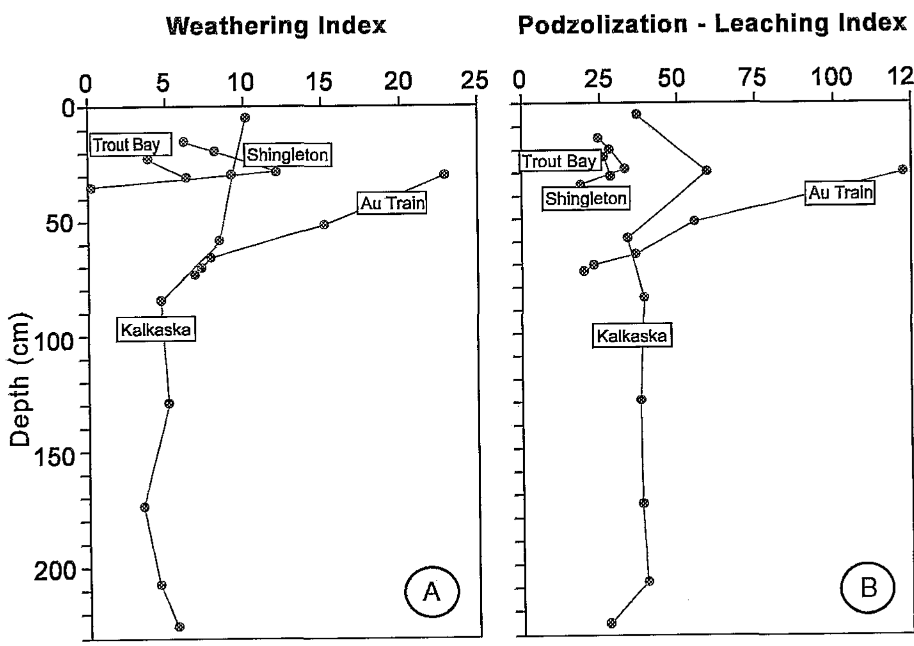

Fig. 3. Depth plots for the four most representative soils studied, related to indices reflecting weathering and podzolization/leaching processes. The indices used here have been developed solely for this study. In both cases, higher values indicate more weathering and/or leaching. (A) The weathering index [(Ti + Zr) / (Ca + Mg + K + Mn + Na + P)] × 100. (B) The podzolization/leaching index [(Si + Ti + Zr) / (Al + Fe)] × 100.

TABLE 2
Chemical data for the four most representative soils studied

Horizon	Depth (cm)	pH (1:1 water)[†]	Organic C (%, based on loss on ignition)	Iron and aluminum contents (%) from extracts[‡]					
				Fe_p	Fe_o	Fe_d	Al_p	Al_o	Al_d
Kalkaska									
Oi	0–3	4.35	21.2	–	–	–	–	–	–
A	3–7	4.34	5.5	0.03	0.04	0.06	0.02	0.02	0.02
E	7–52	5.03	0.1	0.01	0.01	0.01	0.00	0.00	0.00
Bhs	52–65	4.55	0.6	0.18	0.28	0.29	0.12	0.12	0.09
Bs	65–104	4.98	0.3	0.08	0.17	0.19	0.08	0.09	0.09
Bsm	104–154	6.00	0.2	0.05	0.10	0.13	0.08	0.10	0.09
BC	154–193	6.89	0.1	0.04	0.07	0.06	0.05	0.07	0.06
C1	193–221	6.80	0.1	0.03	0.04	0.04	0.04	0.04	0.05
C2	221+	6.94	0.2	0.04	0.18	0.25	0.07	0.15	0.13
Au Train									
Oi	0–3	4.66	32.0	–	–	–	–	–	–
Oa	3–15	3.74	19.6	–	–	–	–	–	–
E	15–45	4.80	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Bhs1	45–58	4.15	1.0	0.26	0.20	0.25	0.11	0.06	0.09
Bhs2	58–73	4.27	1.0	0.40	0.51	0.50	0.12	0.11	0.12
R	73+	4.67	0.8	0.13	0.22	0.31	0.24	0.33	0.31
Shingleton									
Oi	0–2	6.23	27.9	–	–	–	–	–	–
Oa	2–12	6.03	26.2	–	–	–	–	–	–
A	12–18	6.95	1.6	0.07	0.38	0.34	0.06	0.14	0.12
BA	18–21	7.29	0.7	0.23	0.42	0.58	0.13	0.12	0.12
Bs	21–35	7.09	0.6	0.22	0.45	0.35	0.12	0.16	0.11
2R	35+	8.75	–	0.01	0.24	0.15	0.00	0.01	0.01
Trout Bay									
Oa	0–16	6.70	15.8	–	–	–	–	–	–
A	16–30	6.85	4.8	0.28	0.35	0.36	0.21	0.24	0.20
2Cr	30–33	6.90	0.4	0.17	0.24	0.37	0.04	0.05	0.04
2R	33+	–	–	nd[2]	nd	nd	nd	nd	nd

[†]See text for exceptions.
[‡]No data; bedrock sample was not taken.

Zech et al., 1990). Most agree that clay–humus complexes, which form readily in soils of grasslands, are the primary reason for the slow decomposition of organic matter in these soils. However, in the humid soil environments such as exist in PRNL, forest-derived organic matter is normally acidic and the addition of a few bases to the soil system actually facilitates decomposition. This observation is supported by a comparison of the Au Train and Shingleton soils (Fig. 2). Au Train soils, on acid sandstone that provides almost no base cations to the soil system, have thick O horizons and lack a distinct A horizon (Table 1). Starkly in contrast is the Shingleton pedon, which has a thick O + A horizon sequence and a humus-rich B horizon (Table 2); it classified as a Lithic Udipsamment. Many pedons within the Shingleton map unit classify as Mollisols. Worms and other soil macrofauna are abundant in this area, above limestone bedrock, whereas within Au Train map units (on sandstone) soils are impoverished of infauna.

Runge viewed "organic matter production" (the *o* factor) as being intimately tied to base cycling (Runge, 1973). To that, we would add the processes associated with mineralization; we view all of these as being part of the *o* factor. Certainly, in the Shingleton and Au Train soils, these processes are all closely linked. The shallow limestone below the base-poor drift in the Shingleton pedon favors deep rooting, and release of base cations from the weathering limestone also facilitates organic matter mineralization and decomposition; in sum, cycling of bases is rapid and ongoing, largely due to rapid organic matter turnover. Plants on Au Train soils have little reason, except for anchorage, to root deeply. Most of the nutrients in this system are locked up in the thick O horizon due to the acidic, infertile conditions (Table 2) that limit organic matter decomposition; base cycling is minimal (Fig. 2).

Podzolization

The Kalkaska pedon epitomizes the podzolization process; it is the classic upland Spodosol in the region and is the base against which all other podzolized soils are compared. Podzolization is also strongly expressed in the Au Train pedon (Fig. 3B), although it is "compressed" due to the shallow bedrock. Both soils have strong eluvial–illuvial couplets (Table 1). The podzolization–leaching index captures the essence of podzolization, exhibiting high values in these two soils; Shingleton and Trout Bay soils, which are only minimally podzolized, have much lower values (Fig. 3B).

Traditionally, podzolization has long been seen as being driven by organic acids, which form chelate complexes with Fe and Al cations and render these normally insoluble cations soluble, allowing them to be translocated from eluvial to illuvial zones (Buurman and van Reeuwijk, 1984; DeConinck, 1980). When chelated, Fe^{+++} and Al^{+++} are readily translocated in percolating water. The presence of chelated metal rating is generally indicated by high amounts of pyrophosphate-extractable Fe and Al (Table 2).

An alternative podzolization pathway involves inorganic sols of Fe and Al. It has been shown that Al and Fe can exist in Spodosols as amorphous, inorganic compounds such as imogolite and allophane (Anderson et al., 1982, Gustafsson et al., 1995). Lundström et al. (2000) called this general group of compounds imogolite-type materials (ITM). When Al is translocated as a positively charged hydroxy-aluminum–silicate complex, ITM can precipitate in the B horizon due to the higher pH values there. Inorganic, amorphous Al is sometimes assumed to be an indicator of the presence of poorly crystalline aluminosilicates like ITM (Jersak et al., 1995). Higher amounts of inorganically vs. organically bound metals in the soil tend to suggest the presence of ITM. To that end, ratios and differences that have proven to be of some use in detecting ITM in soils include $(Al_o - Al_p)/Al_p$, $(Al_o - Al_p)$, and $(Fe_o - Fe_p)$ (Fig. 4).

Finally, another index of the relative crystallinity of Fe oxides in soils undergoing podzolization is the iron activity ratio: Fe_o/Fe_p (McKeague and Day, 1966; Fig. 4D). For the "control" Kalkaska pedon, and for most of the soils, this ratio is less than three. Higher activity ratio values for the Shingleton soil may indicate that, especially in the lowermost horizon, substantial amounts of iron exist in amorphous forms, that is, not bound in chelate complexes. Other ITM-related indexes tend to suggest that chelate-driven podzolization in the Shingleton soils is no stronger than, or perhaps less important than, podzolization driven by ITM (Fig. 4). In conjunction with this trend, in the Shingleton pedon, ammonium oxalate extracted much larger amounts of Fe and Al than it did in the other soils (Table 2, Fig. 4). The reason for this is unclear, although it may reflect the different nature of the organic acids in the base-rich Shingleton soil, compared to the more acidic environments of the other soils, where fulvic acids may be more abundant. Low podzolization–leaching index values for the Shingleton pedon (Fig. 3B), coupled with its Mollic-like morphology, indicate that podzolization is not particularly active in this soil, and the high ITM-related values in Fig. 4 suggest that this process, weak though it may be, could be at least partially driven by ITM. Lastly, we note that the high ITM "spike" in the lower profile of Shingleton may not necessarily indicate ITM because (1) the data are from the uppermost bedrock layer, and not a soil horizon, and (2) the high value for this ratio is an arithmetic artifact caused when a very small number is in the denominator.

When viewed in their totality, the data in Fig. 4 suggest the presence of ITM, or at least substantial amounts of "active" Fe and Al compounds, in the Au Train soil and perhaps in the lower part of the Shingleton pedon (Fig. 4). In both cases, these compounds seem to be accumulating above the soil–bedrock interface and within the uppermost bedrock. Accumulation of ITM and chelated metals at the bedrock interface is not uncommon in lithic Spodosols (Schaetzl, 1992). The Au Train pedon clearly is undergoing strong podzolization in the traditional "chelate-driven" sense (Fig. 3B), as indicated by high values of Fe_p and Al_p (Table 2). This finding is supported by the Au Train Bhs horizon that has, in at least three of the four depth plots in Fig. 4, negative values for the ITM indicators. Comparable data for the Kalkaska pedon also hover near or slightly above zero, indicating near equal amounts of amorphous Fe and Al compounds, when compared to organically bound Fe and Al (Fig. 4, Table 2). Together, these data suggest that podzolization in the acid, sandy Spodosols of this region is

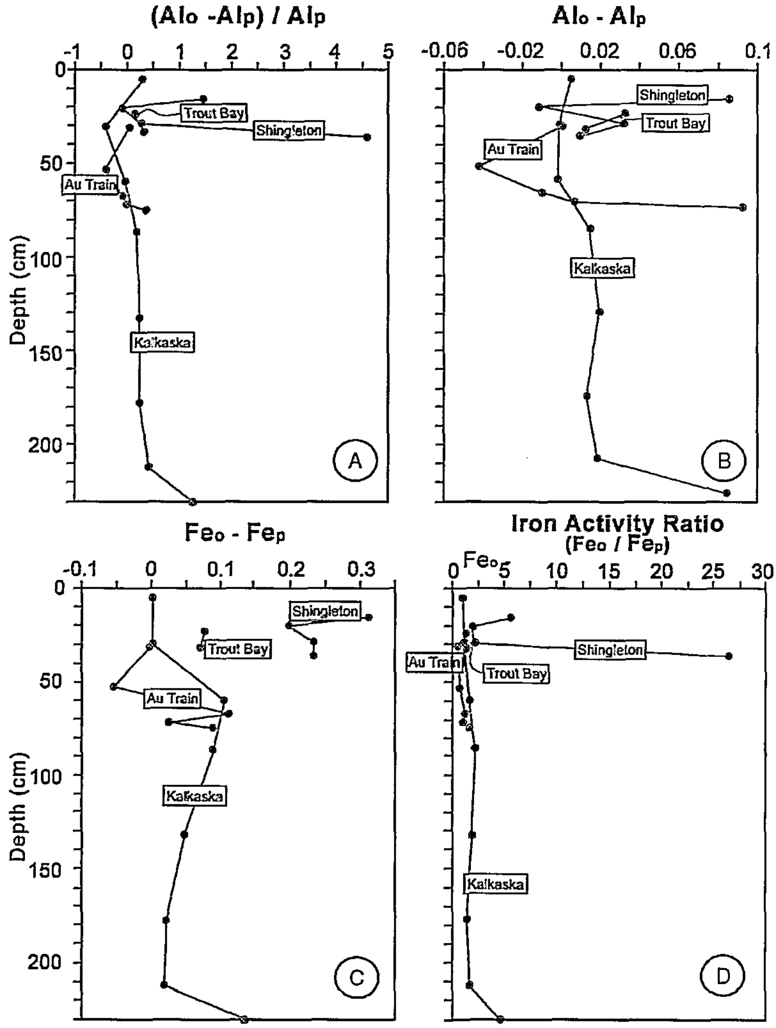

Fig. 4. Depth plots, each intended to indicate the likelihood of "active" podzolization-linked materials, and/or ITM (imogolite-type materials), in the four soils studied. Higher values indicate a greater likelihood of ITM or Fe and Al compounds associated with "active" podzolization. Symbols: Al_o and Fe_o, ammonium oxalate-extractable Al and Fe, respectively; Al_p and Fe_p, sodium pyrophosphate-extractable Al and Fe, respectively.

governed primarily by organic chelate complexes rather than by ITM (Buurman and van Reeuwijk, 1984), but that weaker podzolization in base-rich and organic-rich soils may involve a measurable component of ITM.

Weathering

Using elemental composition as surrogates for mineral weathering, our data suggest that weathering is most intense in soils that have minimal organic matter production (biocycling) and maximal water available for leaching, as suggested by the energy model (Fig. 3A). The Au Train soil, with abundant percolation and minimal amounts of organic matter mineralization, has by far the highest weathering indices (Fig. 3A). Conversely, Trout Bay and Shingleton soils are much less weathered due to a combination of less water available for leaching and more biocycling, both of which lead to higher pH values in the sola of these soils (Table 2, Fig. 3A).

SUMMARY AND CONCLUSIONS

Runge's energy model (Runge, 1973) is considered to be one of the major conceptual–theoretical models in pedology (Johnson and

Watson-Stegner, 1987; Smeck et al., 1983). And yet, it has found limited direct application in soil geomorphology or soil genesis research and is rarely used in mapping. In our study, we highlight the utility of the energy model by using it to help explain the differences in soils that have developed in close proximity, but which display widely different morphologies and pedo-chemistry. In each case, the varying pathways of pedogenesis that these soils have taken can be primarily traced back to water available for leaching or organic matter production, both of which are fundamental precepts of the energy model. (Erosion also plays a role in the genesis of these soils, especially the Trout Bay soil.) The model may be more relevant and applicable in a wider context if the *o* factor included more clearly the processes of biocycling and organic matter mineralization.

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