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Distribution and classification of soils with clay-enriched horizons in the USA

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ABSTRACT

In *Soil Taxonomy* three diagnostic subsurface horizons reflect clay enrichment: the argillic, kandic, and natric horizons. Clay illuviation is recognized in *Soil Taxonomy* at some level in 10 of the 12 orders, including the order (Alfisols, Ultisols), suborder (Aridisols), great group (Aridisols, Gelisols, Mollisols, Oxisols, Vertisols), and subgroup (Andisols, Aridisols, Inceptisols, Mollisols, Oxisols, Spodosols). Forty-four percent of the soil series in the USA contain *taxonomically defined* clay-enriched horizons. However, many other soils contain Bt horizons that do not qualify as an argillic or related horizons. Several soil-forming factors are important in their development, including udic and ustic soil climates, lithological discontinuities, parent materials enriched in carbonate-free clays and coarse fragments, well-drained conditions, backslopes rather than eroding shoulders, and a time interval of >2000 yr or more. The genesis of argillic, kandic, and natric horizons is also dependent on electrolyte concentration, the amount and distribution of precipitation, clay charge, and microfabric.

1. Introduction

Nearly all classification systems recognize clay-enriched subsoils at a high hierarchical level. Some of the most productive soils in the World for food and fiber production have clay-enriched horizons. Clay-enriched horizons are important for the nutrient status of soils, water retention, and geomorphic stability (Hopkins and Franzen, 2003). In *Soil Taxonomy* (ST) (Soil Survey Staff, 2010), Alfisols and Ultisols are defined on the basis of clay-enriched horizons and many Aridisols and Mollisols have clay-enriched subsoils. Argillic and related horizons have been particularly important in soil stratigraphy, relative dating, pedodiversity studies, and climate-change research (Eghbal and Southard, 1993; Frazmeier et al., 1985; Holliday and Rawling, 2006; Karlstrom, 2000; Karlstrom et al., 2008; Kemp et al., 1998; Othberg et al., 1997; Wilson et al., 2010).

Studies of clay-enriched horizons have been conducted in many countries and regions, such as Russia (Fridland, 1958; Rode, 1964), the United Kingdom (e.g., Avery, 1983), Eastern Europe (Bronger, 1991), Australia (Walker and Chittleborough, 1986), Canada (Lavkulich and Arocena, 2011), Argentina (Blanco and Stoops, 2007), and Iran (Khademi and Mermut, 2003; Khormali et al., 2003, 2012). Birkeland (1999) reviewed the genesis of soils with argillic and related horizons, focusing on field and laboratory data, thin-section and scanning electron microscope (SEM) analysis, and mass-balance studies. In summary, clay-enriched subsoils are the result of translocation, in situ formation, and relative loss of clay from the topsoil.

The objectives of this study are to (i) identify the soil taxa in ST featuring clay enrichment; (ii) show the distribution of clay-enriched soils in the USA with clay enrichment; (iii) discuss the relative importance of the soil-forming factors on the development of clay-enriched horizons; and (iv) compare and contrast the pedogenetic processes involved in forming argillic, kandic, and natric horizons.

2. Historical overview of clay-enriched horizons

That fine soil particles moved through the soil profile was recognized as early as the late 1800s (King, 1895; Sibirtsev, 1900). The importance of clay was stressed by Hilgard (1906), who reviewed the physico-chemical properties in relation to soil development and plant growth. At that time, no size boundary for these fine particles was set and the fine soil particles were often referred to as colloids. It was probably at the First International Congress of Soil Science in 1927 that the size limit for clay was set at 2 μm.

Merrill (1906) observed that in soils of humid regions colloidal particles became partially diffused in rainwater, percolated through the soil, and accumulated in the subsoil. He found that almost without exception the subsoils of humid regions have much more clay than the corresponding surface soils. As a result the subsoils are more compact, heavier and less permeable. He also observed that clay eluviation was sometimes accompanied by $CaCO_3$ leaching which could result in the formation of a hardpan. Merrill (1906) distinguished between soils of the humid regions where clay eluviation takes place and soils of the drier regions where such processes are absent. This climatic distinction on percolating water and its effect on movement of soil particles were further developed by C.F. Marbut and resulted in the distinction between pedalfers and pedocals

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(Marbut, 1927). Wolfanger (1930) described pedalfers and named A the horizon of maximum extraction and B the horizon of concentration. He wrote: "The extraction and concentration are brought about in part through eluviation (the mechanical transfer of material), in part by transfer through solution and reprecipitation (chemically) and in part by both processes. Fine grained materials, clay and silt, are mechanically transferred from the upper to the lower horizons."

Robinson (1932) distinguished between two types of eluviaton: mechanical eluviation in which, apart from any chemical differentiation, the finer fractions of the mineral portion of the soil are washed down to lower levels, and chemical eluviation in which decomposition occurs and certain products thus liberated are translocated in true or colloidal solution to be deposited in other horizons. Mechanical eluviation results in the development of a texture profile characterized by a light textured A horizon and a heavy textured B horizon enriched by the finer material from the A horizon, and such soils are common in the southeastern US (Robinson, 1932).

One of the first descriptions of the argillic horizon was by Joffe (1936). He also considered the B as a horizon that is gaining instead of losing as with the A horizon. The B horizon is therefore known as the horizon of illuviation (washing in) or horizon of accumulation. Joffe recognized that the fine particles were mechanically carried from the A to the B horizon and that it will result in a more compact horizon. The B was named an illuvial horizon and Joffe also postulated the idea of new clay formations in the B horizon which enhances the differences in clay content between the A and the B horizon.

The eluvial and illuvial horizon model was well-developed in the first half of the 20th century. The migration processes were well-understood and the concepts were integrated in the classification of horizons and in the classification of the whole soil profile. The Bt horizon (t for *ton*, German for clay) is now integrated in most soil and horizon classification systems. The French developed the concept of the argillic horizon and the formation of coatings (Duchaufour, 1998). Main characteristic of the B horizon are coatings formed of fine colloidal particles deposited and these have been termed cutans. Cutans can be amorphous organomineral complexes termed organans or sesquioxide complexes termed sesquans or cutans can be formed from crystalline clay minerals laid down in parallel orientation in which they are called argillans. Such argillans characterize the Bt horizon of argillic soils (Duchaufour, 1998). An overview of the different horizons in *Soil Taxonomy* (2010) and their approximate conceptual history is given in Table 1.

In the literature, there is some confusion in distinguishing between the Bt horizon and diagnostic subsurface horizons featuring clay enrichment. A Bt horizon "indicates an accumulation of silicate clay that either has formed within a horizon or has been moved into the horizon by illuviation, or both" (Soil Survey Staff, 2010, p. 318). The definition further states: "at least part of the horizon should show evidence of clay accumulation either as coating on surfaces of peds or in pores, as lamellae, or as bridges between mineral grains." However, not all Bt horizons meet the thickness or depth-distribution of clay requirements of diagnostic subsurface horizons with clay enrichment (see below).

In *Soil Taxonomy* (ST), the *argillic horizon* is a subsurface horizon that contains "a significantly higher percentage of phyllosilicate clay than the overlying soil material" and "shows evidence of clay illuviation" (p. 10). The thickness requirement ranges between 7.5 and 15 cm, depending on the particle-size class. There must be evidence of clay illuviation in at least one of the following forms: (i) oriented clay bridging sand grains, (ii) clay films lining pores, (iii) clay films on both vertical and horizontal surfaces of peds, or (iv) thin sections with oriented clay bodies that comprise more than 1% of the section. In addition to a thickness requirement and evidence for clay illuviation, the argillic horizon must have a greater amount of clay than an overlying eluvial horizon; the amount of clay depends on the clay content of the eluvial horizon and ranges from at least 3% (absolute) for eluvial horizons with <15% clay to at least 8% (absolute) for eluvial horizons with >40% clay.

The *kandic horizon* is a subsurface horizon defined in ST on the basis of its thickness (minimum of 15 to 30 cm, depending on soil depth), the depth interval at which the clay increases from an overlying eluvial horizon (50 to 200 cm), the amount of clay increase from an overlying eluvial horizon, an apparent cation-exchange capacity (CEC) of <16 cmol(+)/kg clay (by 1 M NH_4OAc, pH 7), and an apparent effective CEC of <12 cmol(+)/kg clay (sum of bases extracted with 1 M NH_4OAc, pH 7, plus 1 M KCl-extractable Al). The amount of clay increase ranges from 4% (absolute) for eluvial horizons with <20% clay to at least 8% (absolute) for eluvial horizons with >40% clay. It is noteworthy that the kandic horizon does not require evidence for clay illuviation.

In ST the *natric horizon* is comparable to the argillic horizon except that it shows evidence of accelerated clay illuviation by the dispersive properties of Na. The natric horizon has a thickness requirement (7.5 to 15 cm) and evidence for clay illuviation and a clay increase from an overlying eluvial horizon that are comparable to the argillic horizon. In addition, the natric horizon must have either a columnar or a prismatic structure in some part and an exchangeable Na percentage of 15% or more.

In addition to diagnostic subsurface horizons, there are two diagnostic soil characteristics that reflect clay movement: (i) abrupt textural change and (ii) lamellae. An abrupt textural change is "a specific kind of change that may occur between an ochric or an albic horizon and an argillic horizon" (Soil Survey Staff, 2010, p. 15) and is characterized by a considerable increase in clay content within a very short vertical distance. In Australia such soils are called "duplex" and "texture-contrast" soils. A lamella is defined as "an

Table 1
Soil textural horizons and their approximate history and current definition in *Soil Taxonomy*.

Horizon	History	Current definition in *Soil Taxonomy* (abridged)
Bt	Part of the B2 horizon ("zone of accumulation" or "zone of compaction") until 1951. The term was included in the 1951 edition of the *Soil Survey Manual*. However, it does not appear to have been used widely in Europe (Kubiëna, 1950); in the US Baur and Lyford (1957) used "t" to designate clay accumulation in some New England soils. Once the *7th Approximation* (Soil Survey Staff, 1960) was published, the term experienced widespread use.	An accumulation of silicate clay that has formed within a horizon or and has subsequently has been translocated within the horizon or has been moved into the horizon by illuviation, or both. Evidence of clay accumulation by coatings on ped, lamellae, or as bridges between mineral grains.
Argillic	Included in the 7th Approximation in 1960 (Soil Survey Staff, 1960). However, it doesn't appear to have been used in ASA-SSSA-CSSA publications until 1964, when Harpstead and Rust (1964) used the term for some Alfisols in Minnesota, USA. "The Supplement to Soil Classification" was added in 1967, and the term became widely used shortly thereafter.	A subsurface horizon with a significantly higher percentage of phyllosilicate clay than the overlying soil material. It shows evidence of clay illuviation.
Natric	Included in the 7th Approximation in 1960 (Soil Survey Staff, 1960). However, it does not appear to have been used in ASA-SSSA-CSSA publications until 1974, when Sharma et al. (1974) used the term for a Natraqualf in Illinois (USA).	An illuvial horizon that is normally present in the subsurface and has a significantly higher percentage of silicate clay than the overlying horizons. Evidence of clay illuviation that has been accelerated by the dispersive properties of sodium.
Kandic	Introduced in *Soil Taxonomy* between 1985 and 1987 and first appeared in the 3rd edition of *Keys to Soil Taxonomy*.	Subsurface horizon that is dominated by low activity clays and underlying a coarse textured surface horizon.