GENESIS, DISTRIBUTION, AND CLASSIFICATION
OF SODIC SOILS IN OKLAHOMA

By

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CHAPTER I

LITERATURE REVIEW

Introduction

Soils containing enough sodium on the exchange complex to adversely affect soil structure and physical properties fall into the loosely defined category of *sodic soils*. In North America sodic soils cover 10, 748 Ha (FAO, 1993) with 2,590 Ha in the U.S. (Levy, 2000). Sodic soil areas may be negligible in some areas and may occupy up to 50% of the landscape in other regions (Lewis and White, 1964).

Sodicity poses numerous environmental hazards in agricultural, engineering, and urban settings. Decreased water retention and availability, diminished nutrient availability, and impaired biological activity (Sumner, 1995; Swift, 1995) of sodic soils impose serious problems to growth and production of most crops and make farming difficult (Levy, 2000). Structures (dams, bridges, road embankments) built from sodic soils often fail at first wetting and need extensive maintenance (Knodel, 1991). The sodicity also affects the quality of surface and ground waters, which interact with these soils (Swift, 1995). Sodic soils are susceptible to surface sealing, which generates runoff flow and causes surface erosion. The latter leads to sedimentation of streams, which in turn reduces the capacity of a stream to carry water, increases the danger of flooding, and negatively affects aquatic productivity. Enhanced clay dispersivity associated with sodic conditions in the soil can cause piping and tunneling, which may result in deep gully formation. Transport of various contaminants by soil colloidal materials, whether to ground or surface water bodies in runoff, is a serious environmental hazard (Levy, 2000).

Much of the sodicity occurs in the subsoil, making detection and management more difficult. For most sodic soils, sodicity is a natural phenomenon related to the nature of the parent material and subsequent pedogenic processes. There are also sodic soils where sodicity arises from irrigation without proper drainage, forest clearing, and other land management practices that can lead to water logging in soils. It is expected that the area of human-induced sodic soils will increase in the future (Swift, 1995; Levy, 2000).

Complex heterogeneity of sodic soils, emphasized by Gedroitz (1927) and Kellog (1934), causes sodic soil definition and identification problems. The universal theory of sodic soil genesis proposed by Gedroitz (1927) does not explain all variations in sodic soils and has been adjusted to local conditions.

Unlike their saline counterparts, sodic soils have received little attention (Sumner, 1995). Understanding spatial distribution, genesis, and clarifying sodic soil classification requires an extensive knowledge of sodium-affected soil origin, distribution, and evolution and is essential to properly manage sodic soils.

Definitions and Classifications of Sodium-Affected Soils.

History of Sodic Soil Classification

The term "sodic soil" refers to a soil that contains sufficient exchangeable sodium to impair its productivity and may contain excess soluble salts (U.S. Salinity Laboratory Staff, 1954).

Soil scientists have encountered salt-affected soils with unique structure and physical properties. These soils contain an easily erodible A-horizon, impermeable B-horizon which is prone to tunneling and piping due to high dispersion. A sample description of a sodic soil was as follows:

A - usually thin, platy or granular structure;

E (represented in some soils) - light-colored and structureless;

B - often dark-colored, columnar, prismatic or blocky structure with siltans (uncoated sand or silt grains along ped faces), with significantly higher clay content than overlying horizons;

C - included any kind of parent material from consolidated to unconsolidated rock units.

Chemical analysis of sodic soils often revealed high amounts of exchangeable sodium and/or magnesium in the upper B-horizon with reaction (pH) highly variable from highly alkaline to slightly acid. Soluble salt content was also variable.

Sodic soils received a lot of attention starting at the end of 19th century. Hilgard (1918) introduced the term "*alkali*" for terrestrial salty soils in 1906 and called soils containing sodium carbonate "*black alkali*" due to black spots (owing to the dissolution of humus under high alkalinity). Hilgard's (1918) "*white alkali*" term included soils with neutral calcium, magnesium, and sodium salts.

de Sigmond (1926) suggested using the term "*alkali*" for terrestrial salty soils formed under conditions of temporary humidity and the term "*saline*" for soils infiltrated with a salt solution, independently of climatic or genetic soil conditions. As a rule, the alkali soils possessing a high soluble salt content are poor in exchangeable sodium, while alkali soils saturated or nearly saturated with sodium are almost free from any excess of soluble salts (Nikiforoff, 1930).

Nikiforoff (1930) outlined early alkali soil classifications suggested by the Russians. In one of these classifications alkali soils were included in a class of intrazonal soils. Intrazonal soils do not cover any continuous geographical belt and are developed at places where some peculiar, local soil-forming factors are predominant over the general zonal ones. Later soil classifications proposed by Glinka were based on (1) the degree of soil moisture supply and (2) the type of soil formation. Alkali soils were soils with "temporary excessive moisture" supply, and saline soils had an "excessive moisture" supply. Later the alkali group was replaced by "alkali type," and the saline group was replaced by "swamp type" soil formation.

Gedroitz (1927) put alkali soils in a group whose criteria included saturation with bases, and implied an alkali or *Solonetz* type of soil formation. Gedroitzs' (1927) soils with a solonetz type of formation included *Solonchaks*, *Solonetzes*, and *Solods*. S*olon* in Russian means salt. Solonetz means expressing salty properties (FAO, 1988), and Solonchak means much salt (Kelley, 1951). Solod refers to a particular kind of alkali soil, which has been subjected to prolonged leaching following the accumulation of soluble sodium salts. Solonchak, Solonetz, and Solod represent three consecutive stages of an evolution of alkali soils (Gedroitz, 1927). Gedroitz (1927) and de Sigmond (1926) indicated that presence of sodium on the soil exchange complex led to distinct changes in soil morphology and physical properties (described at the beginning of the chapter). Gedroitz (1927) did not set any value for the amount of sodium (Na) on the exchange complex sufficient to cause such changes. Gedroitzs' (1927) term Solonetz included the following three criteria: 1) quantity of exchangeable sites on the absorption complex, 2) ratio between sodium and both calcium and magnesium, and 3) the amount of soluble salts. Under a total absence of soluble salts in the soil even an extremely small amount of sodium on the exchange sites may distinctly affect dispersive properties of the soil (Gedroitz, 1927). Curtin et al. (1994) demonstrated that each soil at any given amount of sodium on the soil exchange complex has a unique threshold concentration of salts, below which the soil disperses.

The order of *sodium soils* of de Sigmond (1938) included "*saline soils*," "*salty alkali soils*," "*leached alkali soils*," "*degraded alkali soils*," and "*regraded alkali soils*" (de Sigmond, 1938). "Saline soils" are soils that accumulate excess salts, but sodium does not comprise a significant part of the soil exchange complex. Soils with not less than 12-15 % sodium on the absorption complex and salts more than 0.20% (by weight) were in the category of salty alkali soils (values were based on physical properties of soils from Hungary). The difference in morphology of "saline" and "salty alkali" soils was practically imperceptible. These two categories corresponded to Russian Solonchak. Soil with salt concentration lower than 0.1-0.20 % by weight was in the "leached alkali" category that corresponded to Russian Solonetz. "Degraded alkali soils" corresponded to Russian Solod. "Regraded alkali soils" were soils that became saline again.

Hallsworth et al. (1953) studying soils in Australia described the differences between Solonetz and related soils affected by sodium as follows:

- Solonetz has a thin bleached A2 (E in modern classification) horizon overlying a characteristic B-horizon of columnar structure in which sodium and magnesium become co-dominant. Hydrogen is either absent or insignificant on the exchange complex in all horizons (soils are neutral to alkaline).
- Solodized Solonetz has a much thicker A2 horizon that has an acidic reaction and a neutral or alkaline columnar structured B-horizon in which sodium content is distinctly lower than in Solonetz.
- Solodic soils have a fairly thick bleached A2 horizon without evidence of the characteristic columnar structure in the B-horizons and have sodium levels below those of the two soils above. From a moderately acid surface soil, the pH usually shows a marked rise with depth.
- Solods have essentially the same morphology as the solodic soils but are acid throughout. Hallsworth (1953) suggested further division of the solodic soils based on color of the A and B-horizons and on presence of calcium carbonate in lower horizons.

In the U.S. classification of 1938 (Baldwin et al. 1938) sodic soils were distinguished in great groups of Solonetz and Soloth, which were included in the Halomorphic suborder of the Intrazonal Order. Morphology, drainage, and vegetation of the soils were the main classification criteria. Solonetzes were characterized by a friable thin surface underlain by a dark hard columnar layer, usually highly alkaline, with halophytic and other plants and improved drainage compared to a Solonchak. Soloths had a thin friable surface over a whitish leached horizon underlain by a dark brown "heavy" textured horizon with mixed prairie and shrub vegetation and improved drainage and leaching compared to a Solonetz.

The scattered distribution of sodic soils is reflected in such terms as *slickspot, alkali spot, panspot, burnout, blowout, buffalo wallow* and was best summarized in the words "smallpox on the face of the steppe" by Russian scientist V. Dokuchaev (Kellog, 1934). The size of a spot varies from 0.6 m to more than 15 m. The terms "burnout" and "blowout" were used in Canadian literature to denote spots with eroded A-horizons. The term "buffalo wallow" was used to name depressions that occur in the North American Great Plains (Barkley and Smith, 1934; Kellog, 1934). These depressions may be barren or they may support meager growth of halophytic and xerophytic plants.

Current Classifications of Sodic Soils.

Russian classification. Current Russian classification (from Kaurichev, 1989) uses sodicity characteristics at different hierarchical levels: genetic soil type or type, genera, and species. The former is the highest taxonomic unit established in Russia (the classification above genetic types has not been fully worked out) and for sodic soils includes Solonetz and Solod (Tables 1.1, 1.2). Solonetz is a soil that contains a large amount of exchangeable sodium and sometimes magnesium in illuvial horizons (B horisons) and salts at lower depths. These soils are characterized by a sharp horizon

TABLE 1.1.

RUSSIAN CLASSIFICATION OF SOLONETZES

Type	Subtype	Genera	Species
Solonetz automorphic (depth to water table >6m, form on saline parent material)	Chernosemi Chestnut Cinnamon semidesert	sodium carbonate, mixed: sodium-sulfate, sodium-chloride-sulfate neutral	by depth of A crusty (A ≤3) shallow (A 3-10cm) Middle (A 10-18 cm) Deep (A >18cm)
Solonetz semihydromorphic (depth to water table 3-6m, form on terrases)	Meadow chernosem, Meadow chestnut, Meadow-cinnamon, Meadow-frozen,	solonchakic – depth to soluble salts 5-30cm episolonchakous – 30-50cm solonchakous –50-100cm endosolonchakous – 100-150cm nonsolonchakous – 150-200cm	residual – ESP ≤10% subnatric – ESP 10-25% mesanatric – ESP 25-40% hypernatric – ESP >40% By degree of solodization
Solonetz hydromorphic (water table <3, formed in floodplains, depressions under grasses)	Meadow chernosem, Chestnut meadow, Cinnamon semidesert meadow, Meadow frozen	solonchak hypersaline mesasaline hyposaline nonsaline (rare) By depth of carbonate and gypsum: epicarbonate - <40cm endocarbonate - >40cm epigypsic - >40cm endogypsic >40cm	Subsolodic Solodic Hypersolodic By structure in B horizon: columnar nutty prismatic blocky

TABLE 1.2.

RUSSIAN CLASSIFICATION OF SOLODS*.

Type	Subtype	Genera	Species
Solod	Meadow-steppe	solonchakous	by depth of A
		solonetzous	by humus content
	Meadow	nonsaline	By degree of salinity:
		noncarbonate	solonchakic – salts in 30cm
	Meadow swamp	nonsolonetzous	solonchakous – salts in 30-80cm

* - from Kaurichev, 1988

differentiation (boundaries). The surface layer is depleted of clay. The upper part of the B-horizon (*solonetzic* horizon) is dark colored with prismatic or columnar structure. The underlying horizon (*undersolonetzic* horizon) is lighter colored with prismatic or blocky structure and commonly contains gypsum or carbonates. Below the B-horizon there is a maximum accumulation of soluble salts. The B-horizon is dispersive and alkaline (Kaurichev, 1989). Salt composition, depth to soluble salts, degree of salinity, depth to carbonates and gypsum are used to distinguish between genera of Solonetz type (Table 1.1). Depth of the A-horizon, amount of sodium on the exchange complex, structure of the B-horizon, and degree of solodization are used to outline different species of Solonetz soils (Table 1.1). Solods are soils formed from Solonetzes by replacing sodium with hydrogen on the exchange complex. The presence of amorphous silica (SiO_2) and exchangeable sodium in the lower horizon characterize these soils. Reaction in the upper horizons is acid or slightly acid, and in the lower horizons it is neutral or slightly alkaline (Kaurichev, 1989). Solods genera and species are recognized based on depth and amount of salts, degree of solonetzity, presence of carbonates, depth of the A-horizon, and humus content (Table 1.2).

Soils of other than Solonetz and Solod types, affected by sodium, are recognized at a genera or species level (Table 1.3). They may carry some morphologic characteristics of the Solonetzes and Solods, or may have an ESP in a range of 3 to 15%.

Rozov and Ivanova (1967a) suggested a higher than genetic type taxonomic unit: *biophysicochemical order*. Solonetzes and Solods are in the order of humate-fulvate-sodium soils, in which sodium along with magnesium and calcium plays the determining

TABLE 1.3

RUSSIAN CLASSIFICATION OF SODIUM-AFFECTED SOILS
(groups other than Solonchak, Solonetz, and Solods).

Genetic Type	Genera	Species
Chernozems[1]	Solonchakic Solodic	
Meadow chermozems	Solonchakous Solonetzous Soloded	
Grey Forest gleyic Soils	Soloded	
Chestnut[2] soils	Solonchakous Solonetzous-soloded Solonetzous Carbonate solonetzous Residual solonetzous	Subsolonetzous (ESP 3-5%) mesosolonetzous (ESP 5-10) hypersolonetzous (ESP >10-15)
Cinnamon semidesert soils[3]	Solonetzous Residual solonetzous soloded Solonchakous	By degree of solonetzity
Cinnamon-brown soils*	Residually solonetzic Ancient salinized	
Gray-cinnamon soils	Solonchakic Solonchakous Solonetzous	
Takyrs	Solonchakic Solonetzous	
Serosems	Solonchakous Secondary Solonchakous Solonetzous*	

TABLE 1.3, cont'd

Genetic Type	Genera		Species
Grey Brown soils	Solonchakous	Solonetzous	By degree of solonetzity By depth of soluble salt
Brown soils	Solonchakous Solonetzous		By degree of solonetzity
Gray cinnamon Brown soils*	Solonetzic Ancient salinized		

[1] - Solonetzous - ESP$\geq$5%, dense solonetzic horizon;
Soloded– elluvial materials in upper B, claytans, humus staining, sometimes presence of exchangeable Na

[2] - Solonetzous horizon – dense B horizon, prismatic structure, claytans;
Soloded horizon – SiO_2 powder on ped faces of platy structure in upper B;
Residual solonetzous– solonetz morphology, exchangeable Na not significant;

[3] - Solonetzous – ESP 3-15%, dense upper B, prismatic structure;
Residual solonetzous solodic – SiO_2 powder, platy structure in upper B, some exch Na;
Carbonate solonetzous – heavy clayey soils, Mg along with Na on exchange complex;

* - from Rozov, Ivanova, 1967b.

role in the composition of adsorbed bases and in which readily soluble salts may be found in all horizons (Rozov, Ivanova, 1967a; Kaurichev, 1989).

U.S. classifications. The investigators in the United States of America (U.S. Salinity Laboratory Staff; 1954) have set up a classification based on the ideas of Gedroitz and de Sigmond. The U.S. Salinity Laboratory classification includes *saline*, *saline-alkali* and *non saline-alkali* soils. Values of an electrical conductivity (EC) and exchangeable sodium percentage (ESP) are used to identify these three classes. Electrical conductivity (EC) of a solution extracted from a saturated soil paste was adopted by the Salinity Laboratory (U.S. Salinity Laboratory Staff, 1954) as the preferred scale for a general use in estimating soil salinity. Soil is considered saline if the saturation extract has an EC value of 4 mmhos/cm (dS/m in modern units) or more (USSL Staff, 1954). Relative concentration of sodium on the exchange complex is expressed as an exchangeable sodium percentage (ESP) (U.S. Salinity Laboratory Staff, 1954). The ESP value of 15 is used as a lower limit for the alkali soils, with soils having an ESP less then 15 defined as non-alkali. The term "saline soils" is used for soils with an EC of saturation extract of more than 4 dS/m at 25°C and an ESP of less than 15%. Usually the pH is less than 8.5. These soils correspond to Hilgard's (1918) "white alkali," "Solonchaks" of the Russian soil classification system, and "saline soils" of de Sigmond. Sodium seldom comprises more than a half of the soluble cations and hence is not adsorbed to any significant extent. The main anions are chlorides and sulfates. Small amounts of bicarbonate may occur, but soluble carbonates are practically absent. Saline soils may contain salts of low solubility such as calcium sulfate (gypsum) and calcium and magnesium carbonates.

The term “saline-alkali” is applied to soils that have an EC of a saturation extract of more than 4 at 25°C and an ESP of more than 15%. These soils are formed in the combined process of salinization and alkalinization. Except when gypsum is present, the drainage and leaching of saline-alkali soil leads to the formation of nonsaline-alkali soil. These soils correspond to “black alkali” of Hilgard, Russian “Solonchaks”, and “salty alklai soils” of de Sigmond.

“Nonsaline-alkali soils” are soils with an EC of a saturation extract of less than 4 dS/m at 25°C and an ESP of more than 15%. The pH of the soils is often above 8.5. The nonsaline-alkali soils correspond to “black alkali” of Hilgard (1918), to “Solonetzes” of Russians (Kaurichev, 1988), and to “leached alkali” of de Sigmond (1938). These soils occur mostly in semiarid and arid regions in small irregular areas, which are often referred to as “slickspots.” With time these soils develop characteristic morphological features (a dense layer with prismatic or columnar structure below the surface) and physical properties (enhanced dispersion and reduced permeability). Irrigation often results in a large sodium content in a soil, which, however, does not have prismatic or columnar structure, but has a low permeability and is difficult to till. In the soil solution of nonsaline-alkali soils, which is relatively low in soluble salts, sodium dominates among the cations. Anions are mostly chloride, sulfate, and bicarbonate.

The reaction (pH) in some nonsaline-alkali soils of western U.S. may be as low as 6. This group corresponds to “degraded alkali soils” of de Sigmond and “Solods” of the Russian system. Such soils occur only in the absence of lime, and the low pH reading is the result of large exchangeable hydrogen. The physical properties, however, are dominated by the exchangeable sodium and are typically those of a nonsaline-alkali soil (U.S. Salinity Laboratory Staff, 1954).

In the present U.S. soil classification (Soil Survey Staff, 1999), sodicity is used at two hierarchical levels - great groups and subgroups. Sodium adsorption ratio (SAR) along with an ESP is used in Soil Taxonomy to define sodic soils. SAR is measured on soil saturated paste extract and is calculated as

$$SAR = Na/((Ca+Mg)/2)^{1/2},$$

where Na, Ca, and Mg are concentrations of sodium, calcium, and magnesium ions, respectively, in meq/L. The equation was proposed by Gapon (Sposito and Mattigod, 1977).

In Soil Taxonomy (Soil Survey Staff, 1999) the term *sodium* is used along with term *natrium,* a Dutch equivalent for sodium. The horizon containing certain amounts of sodium is called *natric horizon* and is a special kind of argillic horizon. Magnesium is considered in the definition of the natric horizon because, as sodium is removed, magnesium follows in the leaching sequence if chlorides are low and sulfates are high. If leaching continues, the magnesium is eventually replaced. According to the definition the natric horizon has, in addition to the properties of an argillic horizon:

1. Either:
   a. Columns or prisms in some part (generally the upper part), which may break to blocks; *or*
   b. Both blocky structure and eluvial materials, which contain uncoated silt or sand grains and extend more than 2.5 cm into the horizon; *and*
2. Either:

a. An exchangeable sodium percentage (ESP) of 15 percent or more (or a sodium adsorption ratio [SAR] of 13 or more) in one or more horizons within 40 cm of its upper boundary; *or*

b. More exchangeable magnesium plus sodium than calcium plus exchange acidity (at pH 8.2) in one or more horizons within the upper 40 cm of its boundary if the ESP is 15 percent or more (or the SAR is 13 or more) in one or more horizons within 200 cm of the mineral soil surface (Soil Survey Staff, 1999).

Classification of sodic soils in the U.S. soil taxonomy is represented in Table 1.4.

Classifications in Australia. In Australian soil classification, suggested by Isbell (1996), sodic soils are recognized at a highest level, Order (Table 1.5). The criteria used to put soils in Sodosols are textural difference between the lower A (occasionally B1) and B2-horizons and properties of the B2-horizon: amount of sodium on exchange complex (ESP), acidity, and plasticity. Further subdivision is based on ESP values. The lower limit of ESP for "natric" Great Group or "sodic" Subgroup is 6% for most soil orders and 15% for Calcarosols and some Vertosols (Table 1.5), the ESP value is based on dispersion properties of the soils. Sodicity that occurs in lower B or in BC horizons is treated at a subgroup level (Table 1.5). Rengasamy et al. (1984) suggested classification of soils based on dispersion and soil solution composition (SAR and total cation concentration) (Fig. 1.1). Rengasamy and Olsson (1991) have proposed a classification of sodic soils based on SAR >3 (corresponds to ESP of 6) as measured in 1:5 soil: water extract. They also stressed the importance of soil electrolyte concentration and pH (Fig. 1.2), emphasizing that the adverse effects of sodicity on soil physical properties are evident only when the electrolyte concentration is below the threshold concentration required for

TABLE 1.4

USA CLASSIFICATION OF SODIC AND SODIUM-AFFECTED SOILS*

Order	Great Group	Subgroup
Alfisols	Natr_alfs - presence of natric horizon	natric - ESP≥7 (SAR≥6) within 40 cm; natric horizon above duripan; ESP≥15 (SAR≥13) within 100cm;
Aridisols	Natr_ids - presence of natric horizon	natric - presence of natric and petrocalcic horizons; natric horizon within 100cm; sodic - ESP≥15 (SAR≥13) within 100cm for at least 1 month a year;
Mollisols	Natr_olls - presence of natric horizon	natric – natric horizon above duripan;
Entisols		sodic - ESP≥15 (SAR≥13) within 100cm for at least 6 months a year; presence of 3% or more fragments of natric horizon;
Gelisols		natric - presence of natric horizon;
Inseptisols	Halaquepts - salic horizon or ESP≥15 (SAR≥13) within 50 cm	sodic - ESP≥7 (SAR≥6) within 100 cm; ESP≥15 (SAR≥13) within 100 cm;
Vertisols		sodic - ESP≥15 (SAR≥13) within 100cm for at least 6 months a year;

* - from Soil Survey Staff, 1999

TABLE 1.5

USE OF SODICITY IN THE NEW AUSTRALIAN SOIL CLASSIFICATION*.

Order	Great group	Subgroup
Sodosols (texture contrast with upper B horizon pH 5.5 or more and ESP≥6)	Subnatric (ESP 6-14) Mesonatric (ESP 15-25) Hypernatric (ESP>25)	
Kurosols (texture contrast, upper B horizon pH<5.5)	Natric (ESP≥6) in upper B horizon	
Hydrosols (prolonged seasonal saturation of profile)	Sodosolic (as for Sodosol definition	Sodic (ESP≥6 in lower B horizon)
Chromosols texture contrast with upper B horizon pH 5.5 or more and non-sodic)		Sodic (ESP≥6 in lower B horizon
Dermosols (no strong texture contrast, structured B horizon)		Sodic (ESP≥6 in lower B horizon
Kandosols (no strong texture contrast, massive B horizon)		Sodic (ESP≥6 in lower B horizon)
Calcarosols (calcareous throughout, no strong texture contrast)		Epihypersodic (ESP≥15 in upper 0.5 m) Endohypersodic(ESP≥15 below 0.5 m)
Vertosols (cracking clay, ≥35%, with slickensides)		Episodic (ESP≥6 in upper 0.1 m) Epihypersodic (ESP≥15 in upper 0.5 m) Endohypersodic (ESP≥15 below 0.5 m)

* - from Isbell (1995)

Class 1. Dispersive soils

- disperse spontaneously, have TCC < (0.16SAR + 0.14) meg/L
- crusting, reduced porosity even under minimum mechanical stress
  non-saline sodic

Class 2. Potentially dispersive soils

- disperse after mechanical shaking (intensive cultivation or raindrop impact)
- electrolyte concentration required to keep soils flocculated varies with SAR
- <u>Class 2a</u>
- Soils from A-horizons with SAR<3 and which mechanically disperse
- Require an TCC of (1.21SAR+3.3) meq/L to maintain flocculation
- <u>Class 2b</u>
- Soils from A-horizons
- SAR>3, TCC to maintain flocculation same as for Class 2a
- Become spontaneously dispersive (Class 1) when leached without the addition of calcium compounds

  <u>Class2c</u>
- Soils from B-horizons
- SAR>3, TCC=(3.19 SAR – 1.7) meq/L to maintain flocculation

Class 3. Flocculated soils

- soils have more than minimum required TCC
- remain flocculated when subjected to rain, irrigation, cultivation
- <u>Class 3a</u>
- SAR>3 TCC> flocculation value – saline sodic
- <u>Class 3b</u>
- SAR<3, TCC> flocculation value – saline, non-sodic
- <u>Class 3c</u>
- SAR<3, TCC close to flocculation value
- Soil is a long-term aim of management strategies

Fig. 1.1. Classification of Soils Based on Dispersion Behavior and Soil Solution Composition. (From Rengasamy et al., 1984) (TCC is a total cation concentration)

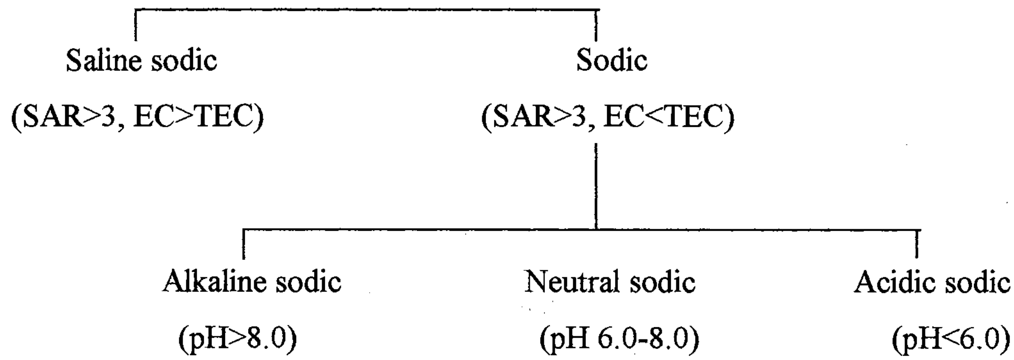

Figure 1.2. Proposed Classification of Sodic Soils by Rengasamy and Olsson (1991) (TEC denotes threshold electrolyte concentration)

the flocculation of the clay fraction. Sumner (1995) stressed that soil behavior is affected by the interrelationship between ESP and the total cation concentration in solution. He suggested classification that divides all soils based on dispersion characteristics (Fig. 1.3).

Classification in Canada (Agriculture Canada Expert Committee on Soil Survey, 1987). In the Canadian soil classification system, sodic soils are differentiated at a highest categorical level of Solonetzic Order, which includes Solonetz, Solodized Solonetz, and Solod great groups. The definition of solonetzic B-horizon accepted in Canada is as follows: a horizon which has 1) the ratio of exchangeable Ca to exchangeable Na is 10 or less, 2) prismatic or columnar primary structure that breaks to blocky secondary structure, 3) dark coatings on ped faces, and 4) both structural units have hard to extremely hard consistence when dry. Solonetz and Solodized Solonetz are distinguished by a well-developed elluvial horizon in the Solodized Solonetz. In Solods the disintegration (prisms break to blocks coated with silicious powder) of the upper part of a former solonetzic B-horizon is seen. Also prismatic structure in B-horizon is not as strong as in Solonetz and Solodized Solonetz. Subgroups are distinguished based on surface color and presence of gleying (Table 1.6).

The Solonetzic subgroup of other orders implies the presence of a solonetzic B-horizon along with general properties specified for the Order and Great Group (Table 1.7).

International Classifications of Sodic Soils. The first international soil classification (FAO, 1974) recognized sodic soils at the highest taxonomic level (Level 1) of Solonetz and on a Level 2 unit of the solodic Planosols. Properties used to distinguish Solonetz

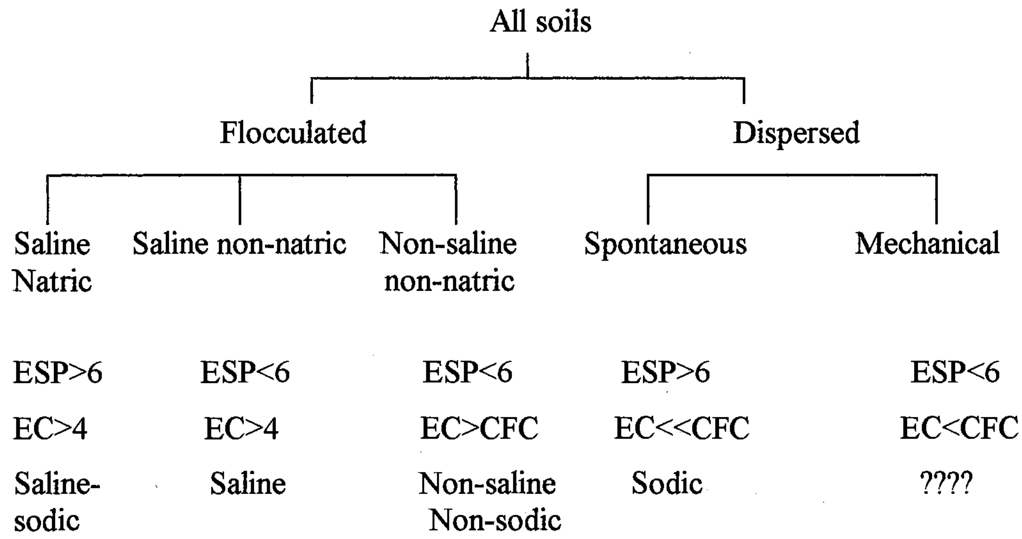

Figure 1.3. Classification of Sodic Soils Proposed by Sumner (1995) (CFC denotes a critical flocculation concentration)

TABLE 1.6

CANADIAN CLASSIFICATION OF SOILS OF SOLONETZIC ORDER*.

Order	Great Group	Subgroup	
Solonetzic	Solonetz	Brown Solonetz	Dark Brown Solonetz
(presence of		Black Solonetz	Alkaline Solonetz
solonetzic B horizon**)		Gleyed Brown Solonetz	Gleyed Dark Brown Solonetz
		Gleyed Black Solonetz	
	Solodized Solonetz	Brown Solodized Solonetz	
		Dark Brown Solodized Solonetz	
		Black Solodized Solonetz	
		Dark Grey Solodized Solonetz	
		Grey Solodized Solonetz	
		Gleyed Brown Solodized Solonetz	
		Gleyed Dark Brown Solodized Solonetz	
		Gleyed Black Solodized Solonetz	
		Gleyed Dark Grey Solodized Solonetz	
		Gleyed Grey Solodized Solonetz	
	Solod	Brown Solod	Dark Brown Solod
		Black Solod	Dark Grey Solod
		Grey Solod	Gleyed Brown Solod
		Gleyed Dark Brown Solod	Gleyed Black Solod
		Gleyed Dark Grey Solod	Gleyed Grey Solod

* - from Agriculture Canada Expert Committee on Soil Survey, 1987
** - definition in text

TABLE 1.7

CANADIAN CLASSIFICATION OF SODIUM-AFFECTED SOILS (orders other than Solonetzic)*.

Order	Great Group	Subgroup
Chernozemic	Brown	Solonetzic Brown Gleyed Solonetzic Brown
	Dark Brown	Solonetzic Dark Brown Gleyed Solonetzic Dark Brown
	Black	Solonetzic Black Gleyed Solonetzic Black
	Dark grey	Solonetzic Dark Grey Gleyed Solonetzic Dark Grey
Gleysolic	Luvic Gleysolic	Solonetzic Luvic Gleysolic
	Humic Gleysolic	Solonetzic Humic Gleysolic
	Gleysol	Solonetzic Gleysol
Luvisolic	Grey Luvisol	Solonetzic Grey Luvisol Gleyed Solonetzic Grey Luvisol

* - from Agriculture Canada Expert Committee on Soil Survey, 1987

soils were the amount of sodium on the soil exchange complex (ESP) and the presence of an E-horizon lacking hydromorphic features. The definition of a "natric B horizon" was the same as the definition of a "natric horizon" given in Soil Taxonomy (Soil Survey Staff, 1999). Sodicity represented by ESP values in a range of 6 to 15% was treated on a phase level. Solodic Planosols differed from Solonetz by the presence of an E horizon with hydromorphic features over a slowly permeable horizon with ESP in the latter of more than 6%. FAO classification (1974) of sodic soils and how it relates to other classifications is shown in Table 1.8.

In the new revised soil map (FAO, 1988) Solodic subunit of Planosols was removed, some subunit names for Solonchaks and Solonetz were changed, and some new subunits were added (Table 1.9). Phases were defined as limiting factors related to surface or subsurface features, which are not necessarily related to soil formation and generally cut across the boundaries of different soil units. The definition of a natric horizon is based only on ESP values.

Another classification of world soils was suggested by International Society of Soil Science (FAO, ISRIC and ISSS, 1998). Sodicity characteristics were used in high-level units, reference soil groups, and low-level units. Solonchaks and Solonetz reference soil groups are subdivided into several low-level units (different from those suggested by FAO in 1988) (Table 1.10). Other reference soil groups include low-level units indicating the presence of sodium in soils that were not classified as Solonetz (Table 1.10). Natric horizon is recognized by texture, higher clay content compared to overlying horizon (certain criteria should be met, depending on absolute clay content), distance within which clay increase occurs, structure, ESP and SAR values, and total thickness.

TABLE 1.8

FAO/UNESCO CLASSIFICATION (1974) OF SODIC SOILS AND ITS RELATION TO OTHER CLASSIFICATIONS*.

FAO	Australia	Canada	USA	USSR
Orthic Solonetz	Solonetz Solodized Solonetz	Solonetz pp.	Natrustalfs Natrixeralf Natrargids Nadurargids	Solonetz pp.
Mollic Solonetz	Solonetz Solodized Solonetz	Black Solonetz Grey Solonetz	Natrallbolls Natriborolls Natrustolls Natrixerolls	Solonets pp.
Gleyic Solonetz	Solonetz pp.	Gleyed Solonetz	Natraqualf	Meadow Solonetz
Solodic Planosols	Solodized Solonetz pp. Soloths	Solods		Solods
Orthic Solonchack	Solonchak	Saline subgroups	Salorthids	Solonchak pp.
Mollic Solonchak	Solonchak	Saline subgroups	Salorthidic Calciustolls Salorthidic Haplustolls	Solonchak pp.
Takyric Solonchak				Takyr
Gleyic Solonchak			Halaquepts	Meadow Solonchaks

* - from FAO (1974)

TABLE 1.9

FAO (1988) CLASSIFICATION OF SODIC SOILS*.

Major Soil Groupings (Level 1)	Solonetz	Solonchak
Level 2 units	Haplic Mollic Calcic Gypsic Stagnic Gleyic Gelic	Haplic Mollic Calcic Gypsic Sodic Gleyic

* - from FAO (1988)

TABLE 1.10

SODICITY AND SALINITY AS USED IN WORLD REFERENCE BASE FOR SOIL RESOURCES*.

Soil Unit	Level	Definition
Solonetz	high	soil having a natric horizon within 100 cm of the soil surface
Solonchak	high	soil having salic horizon starting within 50 cm from soil surface
Natric	low	having natric horizon within 100 cm from the soil surface
Sodic	low	ESP>15% or Na+Mg (exch) >50% within 50 cm from the soil surface
Endosodic	low	ESP>15% or Na+Mg (exch) >50% between 50 and 100 cm from the soil surface
Hyposodic	low	ESP>6% in some subhorizon of > 20 cm thick within 100 cm from the soil surface
Alkalic	low	pH (1:1 in water) $\geq$ 8.5 within 50 cm from the soil surface
Salic	low	having salic horizon within 100 cm from the soil surface
Endosalic	low	salic horizon between 50 and 100 cm from soil surface
Episalic	low	salic horizon between 25 and 50 cm from soil surface\
Hyposalic	low	EC (saturation extract) > 4 dS/m in some subhorizon within 100 cm from the soil surface
Hypersalic	low	EC (saturation extract) > 30 dS/m in some subhorizon within 100 cm from the soil surface

* - from FAO, ISRIC, and ISSS, 1998

Summary. Classifications of the sodic soils differ in critical value set for amount of sodium on the exchange complex; in the U.S. (Soil Survey, 1999), Russian (Kaurichev, 1989) and FAO (FAO, 1974; FAO, 1988; FAO, 1998) classifications it is 15%. In the Australian system ESP value is 15 % only for calcareous soils and is 6% for other soil orders. In the Russian classification, some soils of Solonetz type may have ESP of less than 10%. Such soils are called residual Solonetzes and possibly imply that they were true Solonetzes (had ESP of more than 15%) in the past. In the Canadian soil classification the ratio of exchangeable Ca to Na rather than ESP is involved in sodic soil definition. In different classifications, soils with an ESP between 6 and 15% are recognized as sodic at a lower category name: phase, genera, subgroup, or low-level soil unit. These soils are intergrades to the Solonchaks or Solonetzes. Sodium adsorption ratio is used in the U.S. (Soil Survey Staff, 1999) and FAO (FAO, 1998) classifications to delineate sodic soils, which have an SAR of at least 13. Most differences between sodic soil definitions are in description of morphological features sodic soil should or may have.

The considerable disagreement on the definition of sodicity may be attributed to the youthfulness of soil science (Agriculture Canada Expert Committee on Soil Survey, 1987). Different critical values for ESP (or SAR) may be due to not accounting for the presence of salts in water used to measure hydraulic conductivity (Sumner, 1995). The U.S. Salinity Laboratory Staff (1954) noted that the limit of ESP of 15 must be regarded somewhat arbitrary and tentative.

Solod (leached sodic) soils are underrepresented in some new soil classification schemes. Authors studying sodic soils encounter classification problems when field observations are compared with established taxa (Seelig et al., 1990). In the U.S. literature, sodic soils are often called Solonetzes along with the taxonomic names from the Soil Taxonomy (Soil Survey Staff, 1999). In some articles additions to the existing taxonomy of sodic soils are suggested (Bakhtar, 1973; Edmonds et al., 1986; Seelig et al., 1990a). Wilding et al. (1963) and Munn and Boehm (1983) noted that soils associated with Solonetzes might be misinterpreted as nonsodic while in an advanced soil development stage of sodic soils – Solods. White and Papendick (1961) suggested introducing a bias as to the future development of lithosolic Solodized Solonetz soils so that intergrades with very calcareous sola should be included with the Lithosols and those, which are noncalcareous, should be included with the Solodized-Solonetz. Kelley (1934; 1951) indicated that neither a large content of replaceable sodium, nor high pH values, necessarily accompanies the Solonetz morphology. White (1964a) and Isbell (1996) noted that the presence of columns in clayey soil, presence of bleached horizon, and high pH value are not always evidence of high exchangeable sodium content. White (1964a) suggested that some minor characteristics of the columns are related to the sodium content, but these characteristics are different in each genetic environment.

Isbell (1996) noted that a dispersion test has been used in Australia as a reliable guide to sodicity. Sumner (1995) suggested that focus should be placed on the propensity, which the soil exhibits for dispersion. If management is concerned, new criteria based on soil dispersion needed to be developed to characterize and predict soil physical properties (infiltration, hydraulic conductivity, and hardsetting).

Elucidating processes important in sodic soil genesis will help in clarifying sodic soil definition and classification and lead to proper identification and management.

Genesis of Sodic Soils.

Theories of Sodic Soil Genesis

Properties of sodic soils vary widely, depending on (a) the total concentration and type of soluble salts, (b) the amount of exchangeable sodium of the soil, and c) drainage conditions.

The first scientifically supported theory of the development of alkali (saline) soils was presented by Hilgard in 1906. Hilgard (1918) stated that these soils are the result of rainfall insufficient to leach out the salts that are formed from rock weathering. Alkali soils occur whenever the drainage is slow or restricted usually on level areas of bottomlands or plateaus (Hilgard, 1918). Hilgard (1918) also noted a presence of a hard and impermeable layer formed in subsoil of "black alkali" due to the presence of sodium carbonate. The Romanian scientist de Sigmond (1926) found that alkali soils might contain a small amount of soluble salts and practically be deficient in sodium carbonate with physical properties resembling that of Hilgards' (1918) "black alkali" and of Russian Solonetz. Gedroitz (1927) and de Sigmond (1926) stated that high amounts of sodium on exchange complex accounted for the unique physical properties and morphology of such soils, and that exchange reactions play an important role in the process of sodium accumulation in the soil.

The Russian name of *Solonetz* was accepted widely for a nonsaline alkali soil. The first theory of Solonetz origin was proposed by de Sigmond (1926) and K.K. Gedroiz (1927). The theory requires the presence of a water table, either permanent or ephemeral, close enough to the soil surface to be affected by evapotranspiration, with a consequent upward convective movement of sodium, an arid or semiarid climate, and periods of temporary excessive moisture interspersed with dry periods (de Sigmond, 1926; Gedroiz, 1927). The classic theory views solonetz soils as one stage in the evolution of the alkali soils that may be summarized as follows (de Sigmond, 1926; Gedroitz, 1927; Kelley, 1934; Kelley, 1951; Fitzpatrick, 1971; Johnson et al., 1985):

1. *Non-saline, non-sodic soils.* In these soils the base exchange is saturated with the divalent cations, the colloids are in the flocculated state, and the soil is easy to till and has a good permeability.

2. *Solonchak (Saline soil).* These soils have an excess amount of soluble salts. The process of salt accumulation in the soil is called *salinization.* The original source of all salt constituents is weathering of primary minerals. But, there are only few instances where sufficient amount of salts accumulated in place from this source alone to form a saline soil. Most commonly salts in the soils are transported and originate from (1) sedimentary rocks deposited at the bottom of the sea or salt lake, (2) atmospheric dust or precipitation, (3) irrigation water, (4) saline ground water, (5) volcanic activity, or (6) biological activity. The present position of salts in the profile is due to (1) drying up of old inland seas or arms of present oceans, (2) salt deposition into lowlands by streams, or (3) capillary rise and surface concentration of salts in soils usually from high water table (Burgess, 1928). Salt accumulation may be caused by (1) high water table, so salts cannot be removed by natural drainage, (2) impervious subsoil preventing leaching, (3) rapid evaporation of soil moisture, so salts washed downward by a rain are brought to the surface again by capillarity, and (4) various combinations of the above three factors. An

annual repetition of wetting-drying cycles causes considerable amounts of the salts to accumulate at or near the surface. In general saline soils are found in places where the ground water is close enough to the surface (usually less 3 m in a dry season), or has been previously to permit rise by capillarity of water together with dissolved salts into the topsoil where an evaporation takes place. Ordinarily, the salts are leached from higher elevations in the drainage area and become concentrated wherever the drainage water evaporates. There may be a great variation in concentration and composition of the drainage water. This variation can vary significantly within only a few meters. Salts in the ground water originate from igneous rocks or layers of salt-bearing sedimentary rocks. The salt composition of drainage waters is related to the kind of geological formation from which the drainage water has come or through which it has passed. The ground water of the arid lands is commonly more saline than that of the humid regions.

Usually some portion of divalent cations on the soil exchange complex of saline soils is replaced by monovalent cations, especially sodium. The process is called *alkalinization*. These soils are called "saline-alkali" (U.S. Salinity Laboratory Staff, 1954) or "salty alkali" (de Sigmond, 1938). Alkalinization depends on type of sodium salts. In case of neutral salts of chloride and sulfate the reaction is as follows:

$$\mathrm{Coll}_{Ca}^{Mg} + 4\,\mathrm{NaCl} \Leftrightarrow \mathrm{coll}\begin{smallmatrix}Na\\Na\\Na\\Na\end{smallmatrix} + \mathrm{CaCl_2} + \mathrm{MgCl_2}$$

Sodium displaces only a part of the exchangeable calcium and magnesium. This can happen only in the case of a high concentration of sodium in the soil solution as compared with the concentration of soluble calcium and magnesium together. However, if there is a slow rate of lowering of the water table, then the ground water will add new amounts of sodium salts – by capillary rise through the soil stratum followed by evaporation during the hot season. During the rainy season, soluble salts are leached, and the amount of exchangeable sodium gradually increases.

When sodium occurs in soil as soda, its penetration on the exchange is more intensive:

$$\text{coll}^{Mg}_{Ca} + Na_2CO_3 \rightarrow \text{coll}^{Na}_{\substack{Na\\Na\\Na}} + CaCO_3\downarrow + MgCO_3\downarrow, \tag{1}$$

where $\downarrow$ means precipitation

Kelley and Brown (1921) showed that alkaline salts are either adsorbed or held in loose chemical combination by soils to a greater degree than the neutral salts. Soils with different contents of adsorbed sodium are formed by periodic salination with sodium salts. If the soil contains soluble calcium, alkalinization will not occur. The presence of excess salts prevents the hydrolysis of the sodium from the exchange and keeps colloids flocculated.

3. *Solonetzes ("nonsaline alkali," "leached alkali").* Solonetzes are soils that previously contained excess amounts of sodium salts. These soils have a relatively high percentage of exchangeable sodium and a low percentage of soluble salts. This is the result of natural leaching of soluble salts (*solonization*) after the water table has receded sufficiently for leaching to be effective. In the presence of calcite or gypsum the resulting soil may be free of exchangeable sodium. When soda occurs in soil it can become a Solonetz without the Solonchak stage (Gedroiz, 1927; Rode, 1955) as shown in equation (1). Given a large content of sodium on the soil exchange complex, removing of salts causes increased hydrolysis of the sodium resulting in a highly alkaline soil reaction (pH). As the soluble salts are leached, the colloidal particles tend to disperse. The result

is that clay from the surface is translocated down, and a dense subsoil horizon (natric horizon) is formed. Given enough time, certain morphology and physical properties develop. The A-horizon of a Solonetz is usually structureless. The upper B-horizon often has maximum alkalinity and is of black color with columnar or prismatic structure. This horizon is clayey and often very dense and impervious. The lower B-horizon often contains calcium carbonate, gypsum, and soluble salts.

4. *Solod ("degraded alkali")*. Solonetz soils are comparatively rapidly leached even in a relatively arid climate. Upon continued leaching, exchangeable hydrogen increases and soil pH decreases. Depleted of clay a siliceous powder (bleached silt grains or siltans) may be seen as light-colored coatings on or around the tops of soil structural units. The process is called *solodization*. Solods often have a zone of elluviation and an E-horizon. The profile of these soils may still exhibit Solonetz morphology. The presence of $CaCO_3$ prevents solodization (Gedroitz, 1927; Kelley, 1934). In this case, during leaching, calcium rather than hydrogen displaces the absorbed sodium on the soil exchange complex. Rode (1955) suggested that vegetation contributes to the recycling of calcium from the lower parts of the profile into upper horizons. Many Solods occur in shallow depressions and are moist for longer periods than the surrounding areas. They often support communities dominated by trees (birch or aspen in high latitudes), have gleying at the top of B-horizon (Fedorin, 1960; Fitzpatric, 1971), and are surrounded by grass vegetation on non-Solod soils.

There is not a sharp line between various stages of alkali soil evolution, and this continuum has given rise to conflicting statements, particularly in regard to the Solonetz. Soils with Solonetz morphology that contained considerable soluble salts distributed throughout the greater part of the profile were found (Kelley, 1951). These soils were considered to be leached soils that have developed the characteristics of Solonetz, but which later became resalinized by a rise in a ground water (Kelley, 1951). Solonetz soils in some parts of the world may have H^+ ions as a substantial part of the exchange complex and hence a pH less than 7 (Kelley, 1934; U.S. Salinity Laboratory Staff, 1954). According to Gedroits (Kelley, 1934), the E-horizon, characterized by lack of structure means that alteration of Solonetz has already taken place. This alteration progresses in two directions: a) saline soils containing $CaCO_3$ will, upon leaching, pass into Solonetz and then to non-saline, non-sodic soil; b) in the absence of $CaCO_3$ leaching produces leached Solonetz (Solod) with excessive amounts of exchangeable sodium in the lower horizons (Gedroitz, 1927). Nikiforoff (1930) and Kellog (1934) stated the presence of all possible stages between Solonchak and Solod (Fig.1.4). The profound physical alteration pointed out above gradually develops over a long period of time, and these physical changes may not be completely overcome by the mere replacement of sodium by calcium on a soil exchange complex. Some soils may still have Solonetz morphology but levels of exchangeable sodium are that of non-sodic soils (Fitzpatric, 1971; Soil Survey Staff, 1999). Many soils with Solonetz morphology have magnesium as predominant cation on the exchange. These soils are called *magnesium Solonetz* (McGregor and Wyatt, 1945) and may be found in many parts of the world (Gedroitz, 1927; Kelley, 1934; Mitchel and Riecken, 1937; McGregor and Wyatt, 1945; Arshad and Pawluk, 1966; Soil Survey Staff, 1999). Kelley (1934) stated that alkali soils in America are predominantly calcareous, and among them the extensive development of Solods is not to be anticipated.

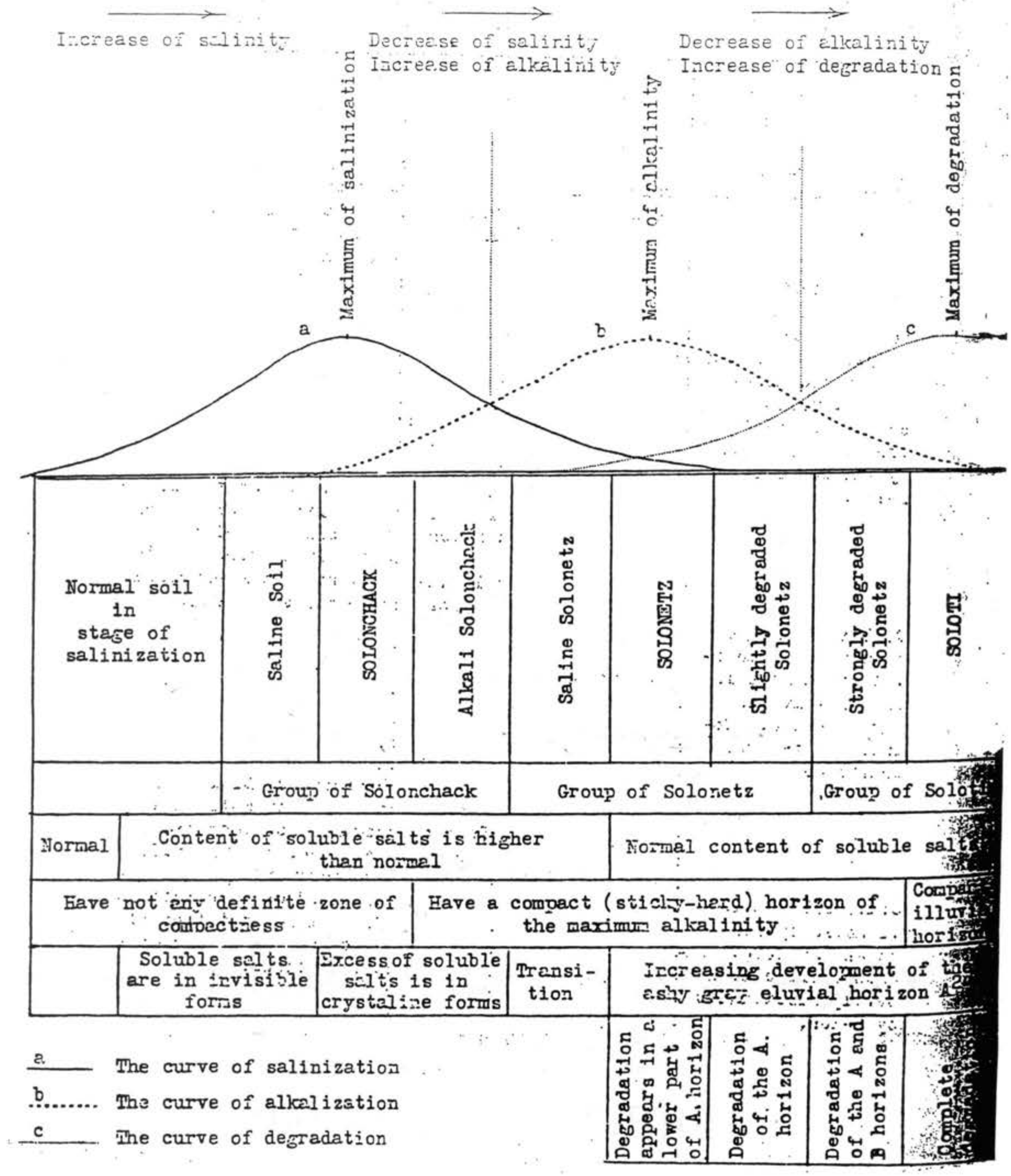

Fig. 1.4. Groups of Solonchak, Solonetz, and Soloth Soils. From Nikiforoff (1930)

Some of the consequent studies supported and evolved the classic theory of sodic soil genesis, which requires the presence of a water table shallow enough to be effected by evaporation and to effect soil drainage conditions (Kellog, 1934; Kelley, 1934; Murphy and Daniel, 1935; MacGregor and Wyatt, 1945; Bentley and Rost, 1947; Kelley, 1951; Westin, 1953; Wittig and Janitzky, 1967; Arshad and Pawluk, 1966; Fullerton and Pawluk, 1987; Hopkins et al., 1991; Miller and Pawluk, 1994; Seelig and Richardson, 1994).

Kellog (1934) described two types of Solonetz that may occur depending on the source of salts: uniform and complex. The former is developed in ponded areas usually from parent materials of heavy clay either of a lacustrine or an alluvial origin. The latter, the most common, develops due to capillary rise of salts from the water table and occurs as "Solonetz-complex," which include alkali soils in different transitional stages: Solonchaks, Solonetz, and Solods. Solodized and solonized soils are found in places of better leaching and drainage (Nikiforoff, 1930; Mitchel and Riecken, 1937; Bentley and Rost, 1947; Westin, 1953; Arshad and Pawluk, 1966; Seelig et al., 1990a). Westin (1953) and Arshad and Pawluk (1966) showed that salt-affected and normal soils are formed from the same saline parent material. Whittig and Janitzky (1963) demonstrated that sodic soils might form in the rim positions as a result of an upward migration of sodium bicarbonate formed due to microbiological reduction in inundated soils with a high water table and a high organic matter content. Topographic position and seasonal fluctuations of the soluble salts and exchangeable acidity in the B-horizons were shown to play a major role in the genesis of soils in the Solonetzic catena of Alberta, Canada (Miller and Pawluk, 1994). Seelig and Richardson (1994) pointed to the importance of lateral water movement and the presence of coarse-textured substrata, which creates pockets of saturation at distinct localities on all landform positions. The evaporation from these pockets led to salt accumulation and formation of sodic soils. Perched water table formed due to physical properties and configuration of buried erosional surfaces, and overlying sediments resulted in intense local weathering of sodium-bearing feldspars in loess and lead to a sodic soil formation in Nebraska (Lewis and Drew, 1973).

Besides the presence of a shallow water table, some researches pointed out the significance of lateral moisture movement in sodic soil genesis in the absence of shallow water table (Lewis et al., 1959; Wilding et al., 1963; Munn and Boehm, 1983; Johnson et al., 1985; Reid et al., 1993). Munn and Boehm (1983) showed that water moves in response to matric and osmotic potential gradients into slickspots from the surrounding areas. Differential redistribution of salts and/or sodium occurs due to the surface microtopographic differences (Reid et al., 1993), different permeability (Wilding et al., 1963), configuration (Munn and Boehm, 1983), or properties (Lewis et al., 1959) of underlying bedrock. In South Dakota, development of Solodized Solonetz, without the aid of fluctuating water table from shallow soils on steep slopes with low amounts of calcium, was recorded (White and Papendrick, 1961). Other studies have concluded that the natric horizon formed through deposition of salt dust from nearby playas (Ballantyne, 1978; Peterson, 1980; Reid at al., 1993). After deposition, the salts and the clay from the dust moved downward and accumulated in the subsoil to form a natric horizon. In absence of a water table, the slickspot development often starts from the erosion (Murphy and Daniel, 1935; White, and Papendick, 1961; White, 1964; Munn and Boehm, 1983; Johnson et al., 1985; Hopkins et al., 1991; Reid et al., 1993). The erosion may be caused by wind (Lewis and White, 1964; Johnson et al., 1985; Hopkins et al, 1991) or animal activity such as sheep grazing or gopher mounding (Reid et al., 1993). A slickspot is formed by exposing the clayey sodic subsoil horizons to the surface (Lewis et al., 1959; Lewis and White, 1964; Johnson et al., 1985; Hopkins et al., 1991) or by redistribution of salts (Reid et al., 1993). Several authors attributed numerous depressions that exist throughout the North American Great Plains to historic bison wallowing (Barkley and Smith, 1934).

The effect of irrigation waters on development of alkali soils was pointed out by several scientists (Hilgard, 1918; Harper and Stout, 1950; Reed, 1962; Levy, 2000). Land management practices that can lead to waterlogging, such as forest clearing, yield sodic soil formation (Levy, 2000).

Various models of the sodic soil genesis reflect the variety of conditions and processes that may interact to produce such soils. The sources of sodium and processes that result in accumulating sodium in the upper soil horizons are different in various locations. Theories of sodic soil genesis must be modified to reflect local climate, landform, and material in which the soil was formed. For most sodic soils, sodicity is a natural phenomenon related to the nature of the parent material and subsequent pedogenic processes driven mainly by the interplay of moisture and temperature. Among the environmental conditions that promote the formation of sodic soils are the presence of shallow saline ground water, the occurrence of perched water table within 1 m of the soil surface, impeded drainage, low slope gradients, and textural discontinuities during deposition of sediments such as eolian, glacial, or alluvial materials (Levy, 2000).

Origin of Salt and Sodium in Soils

Salt and sodium in sodic soils may originate from in situ mineral weathering (Wilding et al., 1963; Lewis and Drew, 1973), capillary rise from a water table (Gedroitz, 1927; de Sigmond, 1928; Kellog, 1934; Fullerton and Pawluk, 1987; Hopkins et al., 1991; Miller and Pawluk, 1994; Seelig and Richardson, 1994), or eolian deposition (Ballantyne, 1978; Peterson, 1980; Reid et al., 1993). Solonetzes from different locations contain various sodium salts, which may account for development of sodic soils. In Oklahoma, the predominant salt in sodic soils is sodium chloride (Reinsch, 1979). Sodium sulfate (Arshad and Pawluk, 1966), or sodium bicarbonate and sodium sulfate (Fullerton and Pawluk, 1987; Miller and Pawluk, 1994) are the principal salts in sodic soils of Alberta Province, Canada. Soda salinity is mostly a feature of the steppe and forest-steppe zones, being the extreme northern variant of the manifestation of salt accumulation: the belt of soda lakes, of soda-Solonchaks, and of soda-Solonetz can be traced in northern Eurasia and North America (Bazilevich, 1965).

The Age of Sodic Soils

The length of time of the natural sodic soil formation from exposed parent material can be less than 2000 years (Peterson, 1980). Natric horizons can form relatively rapidly in low-gravel, high carbonate, clay-containing parent materials under the dispersive influence of sodium. Many sodic soils occur on sediments no older than late Pleistocene or even Holocene. Alexander and Nettleton (1977) showed that sodic soils could form under today's climate in less than 6,600 years. Irrigation may render high salt and sodium content to a soil in only three months (Reed, 1962).

Sodic Soils in Oklahoma

In Oklahoma, processes of salinization and or alkalinization are only of minor importance (Gray and Galloway, 1959). Sodic soils cover only about a 3% area of Oklahoma (USDA/NRCS Soil Surveys). In Oklahoma, sodic soils may occur as (1) saline –alkali salt flats in alluvial deposits or on flood plains; or (2) alkali spots (slick spots) (Reed, 1962). Slickspots, located mostly in central and eastern Oklahoma, are salt free at the surface, while saline-alkali soils have a salty crust when dry and are located predominantly in central and western Oklahoma (Harper and Plice, 1949). Reinsch (1979) found that sodic soils with external drainage were dominated by sodium chloride and ones in depressions had sodium sulfate as a main anion. Mutter (1982) found sodic soils on level uplands and in lowlands with non-saline, non-sodic soils on adjacent slopes.

Several factors of sodic soil formation in Oklahoma are presented in the following literature: (1) soil compaction due to long-term bison use (Barkley and Smith, 1934): (2) accumulation of sodium salts in the sediments laid down by a receding sea (Murphy and Daniel, 1935); (3) impeded drainage resulting in accumulation of salts and exchangeable sodium (Harper and Plice, 1949; Singh, 1959; Gray and Halloway, 1959); (4) "perched" water table above an impervious soil horizon with concomitant evaporation of a salt-laden water (Reed, 1962); (5) salt-saturated Pennsylvanian and Permian shales

(Reed, 1962); (6) oil well salt-water brines released to the natural drainage and evaporation ponds (Reed, 1962); (7) saline irrigation waters (Harper and Stout, 1950; Reed, 1962); (8) saline ground waters (Mehta, 1954; Stewart, 1969); (9) weathering of sodium-rich feldspars in non-salty soils (Bakhtar, 1978); (10) residual sodium in parent material on uplands (Mutter, 1982); (11) insufficient moisture (Gray and Galloway, 1959).

CHAPTER II

REGIONAL-SCALE VARIABILITY AND CLASSIFICATION OF SODIC SOILS IN OKLAHOMA

Abstract

Inconsistent definitions, and hence classification, of sodic soils attribute to their tremendous variability and account for classification problems encountered when field observations are compared to established taxa. This study examined the role of soil forming factors in sodic soil variability and suggested a revised soil classification. Soils representing key sodic soils were sampled across Oklahoma. Each profile was described in the field and was characterized in the laboratory. The spatial distribution of sodic soils depends on parent material, while particular characteristics of sodic soil horizonation reflect climatic setting. There is a gradual change in sodic soils properties across the state along mean annual precipitation and annual lake evaporation gradient expressed as Thorntwaite annual P-E index. Sodic soils in areas with high P-E index showed characteristics of leached soils based on presence of redoximorphic depletions, greater depth to carbonates, greater depth to high soluble salt content and high SAR, and lower surface pH, compared to soils in regions with lower P-E index. Local differences are attributed to 1) ground water, parent material, and underlying bedrock composition; 2) drainage conditions that depend on presence of shallow ground water or impermeable underlying bedrock; and 3) proximity to salt carrying streams. Areas with high P-E index have conditions that result in creation of all stages of sodic soil development from saline-

sodic through sodic to leached sodic. In contrast, regions with low P-E index have only the first stage of sodic soil development, saline sodic soils. The proposed revised classification of sodic soils reflects sodic soil variability caused by moisture conditions. New sodic and solodic subgroups for Hapludalfs, saline subgroup for Natrudalfs and Natrudolls, non-saline, saline, and salic subgroups for Natrustolls and Natrustalfs are suggested.

Introduction

The variability of soils across the world is the result of interaction of processes that are controlled by soil forming factors: parent material, climate, biota, topography, and time (Jenny, 1941; Brady and Weil, 1996). Each set of these 5 factors produces a unique soil. As stated by Simonson (1959), every soil type has a characteristic region of occurrence (zonality). One of the important models of soil variability is that specific soils are associated with specific landforms, and soil patterns are repeating and predictable (Simonson, 1959; Ruhe, 1956; Daniels, and Hammer, 1992; Young and Hammer, 2000). Another concept states that soils vary with variation of soil forming factors (climate, organisms, topography, parent material, and time) (Westin, 1976; Ciolkosz et al. 1989; Birkeland, 1999). The effect of climate has been considered to be the most important (Brady and Weil, 1996) as it determines the amount of moisture in the soil. Many soil classification schemes were based on climate and processes thought to be related to climate (Birkeland, 1999). Variation of soil properties and processes associated with climatic gradient was called pedogenic gradient (Tedrow, 1977). Birkeland (1999) noted that in spite of prevailing effect of climate in the gross worldwide distribution of soils, the other four factors are equally important in describing soil variability on a landscape. Each soil class is characterized by a certain set of factors that affect its distribution. Different soil forming factors (Ciolkosz et al. 1989) or processes (Smeck et al., 1983) are important in determining the occurrence of various soil orders. Westin (1976) considered climate to have a regional effect while parent material has local effect on soil variability and distribution.

This study focuses on a broad group of soils having a large amount of sodium and defined as soils with natric horizon (natric Great Groups) in Soil Taxonomy (Soil Survey Staff, 1999), nonsaline and saline alkali soils (U.S. Salinity Laboratory Staff, 1954), Solonetz (Baldwin, 1938; Agriculture Canada Expert Committee on Soil Survey, 1987; FAO, 1988; Kaurichev, 1989; FAO, ISRIC and ISSS, 1998), and Sodosols (Isbell, 1996). Natric B-horizon is a clay-enriched impermeable dispersive layer with columnar or prismatic structure and often with a bleached layer above. To explain the tremendous variability in sodic soil properties, a cycle of Solonetz soil formation intimately related to moisture condition was proposed by Gedroitz (1927), Sigmond (1926), and Kellog (1934). The soil starts as saline-sodic and upon improved drainage and leaching gradually transforms into sodic and then leached sodic. Soil of different development stages may occur on a same landscape (Kellog, 1934; Nikiforoff, 1930; Miller and Pawluk, 1994). Gedroitz (1927), de Sigmond (1927), Kelley (1934), Kelley (1951), Fedorin (1960), Fitzpatrick (1971), Johnson et al. (1985); Seelig et al. (1990a; 1990b; 1991), and Seelig and Richardson (1994) stressed the determining effect of upward water movement from water table while Wilding (1963), and Munn and Boehm (1983) suggested that in the absence of a shallow water table, lateral water movement plays an important role in sodic soil genesis and variability.

Several attempts have been made to explore regional and local variability of sodic soils in Oklahoma. Gray and Halloway (1959) noted that distribution of sodic soils is intimately linked to parent material and climate. Reed (1962) classified sodic soils that occur in Oklahoma as saline –alkali salt flats in alluvial deposits or on flood plains along major rivers and as alkali spots (slick spots). Reed (1962) also pointed to human impact, such as irrigation and oil well salt-water brine release, in sodic soil formation. Harper and Plice (1949), and Singh (1959) found that slick spots located in central and east Oklahoma are mostly salt free at the surface while saline-alkali soils with a salty crust are located predominantly in south central and west Oklahoma. Bakhtar (1973) and Mutter (1982) studied sodic soil toposequence in central and north central Oklahoma.

Soil variations in properties, distribution, and genesis are reflected in different classification schemes (Westin, 1976; Birkeland, 1999), which are appropriate tools to use when discussing soil distribution and variability (Ciolkosz et al., 1989). Inconsistent definitions, and hence classification of sodic soils, attribute to their tremendous variability and account for classification problems encountered when field observations are compared to established taxa (Seelig, et al., 1990). Often leached sodic soils (Solods) are misinterpreted as non-sodic (Wilding et al., 1963; Munn and Boehm, 1973). Several attempts have been undertaken to improve and extend sodic soil classification. White and Papendrick (1961) suggested considering future development of sodic soils while classifying. Seelig et al. (1990a; 1990b; 1991) and Seelig and Richardson (1994) suggested that soil water regime account for variability of soils under question and should be used to improve sodic soils classification. Edmonds et al. (1986) proposed to broaden the definition of morphologic properties of the natric horizon.

This study presents sodic soil development in a variety of parent materials under a broad range of climatic parameters. The objectives of the study were (1) to determine the effect of the climate on the distribution and properties of sodic soils in Oklahoma, (2) to reveal factors other than climate that determine sodic soil variability, and (3) to expand sodic soil classification by using soil properties that reflect soil moisture conditions.

Materials and Methods

Description of the Study Area

Geology. Oklahoma lies entirely in the Mississippi River basin, and its surface is, in general, a plain that slopes to the southeast (Snider, 1917). General geology of Oklahoma is represented on Fig. 2.1. Most of the outcropping rocks in the western part of the state are Permian age shallow marine, deltaic, and alluvial deposits of red sandstone and shale, with conspicuous gypsum layers and salt deposits (Snider, 1917; Ward, 1961; Jordan and Vosburg, 1963; Johnson, 1979). The central part of the state is overlaid by marine limestone, sandstone, and shale with Permian-Pennsylvanian transitional fossils. Bedrock of the eastern part of the state consists of marine shale, with interbedded sandstone, limestone, and coal deposits. The southeastern part of Oklahoma has outcrops of non-marine sand and clay, and marine limestone and clay (Oklahoma

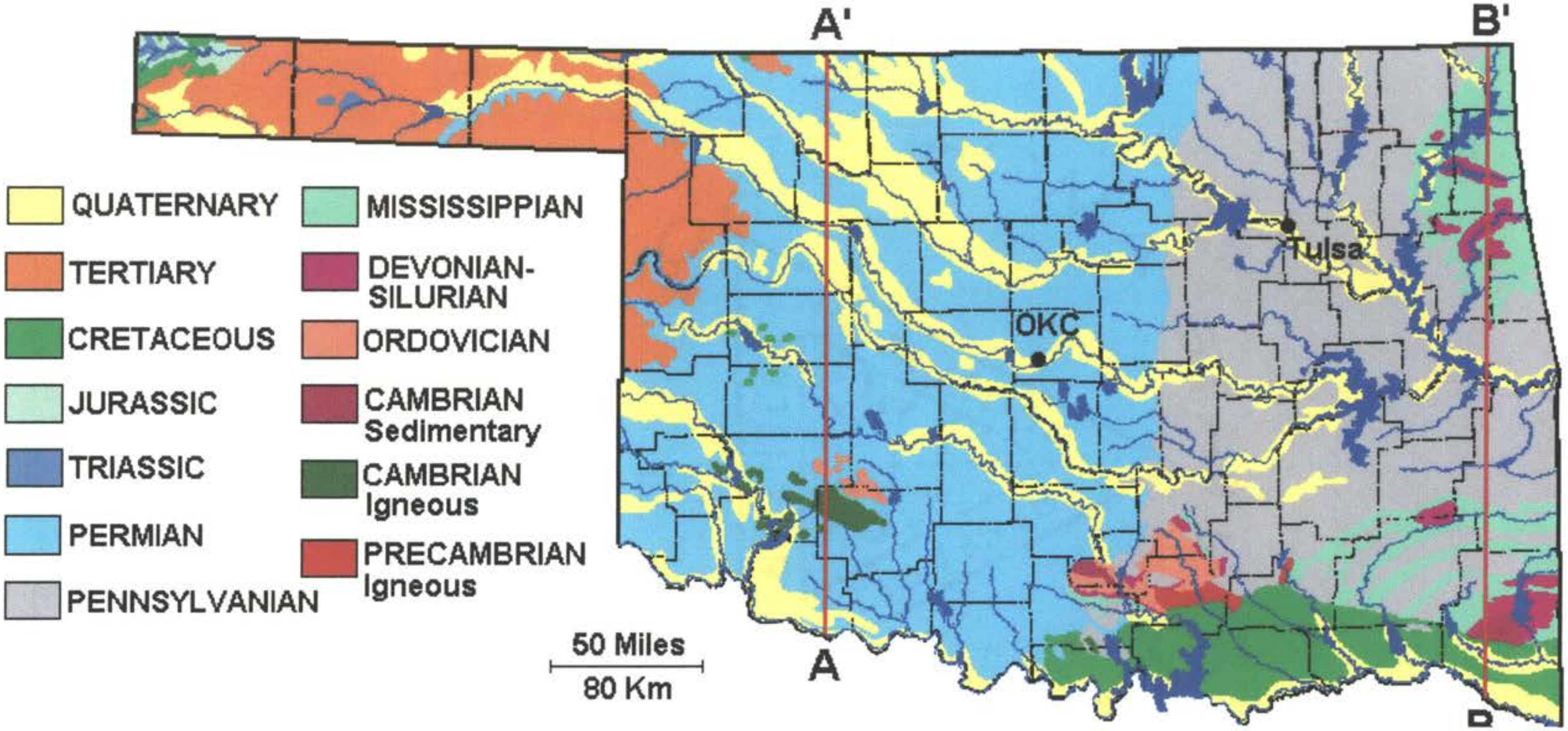

Fig. 3.1. Generalized Geologic Map of Oklahoma (Map modified by T.W. Furr after Branson and Johnson (1979), WWW version by J. Anderson)
Source: http://www.ou.edu/special/ogs-pttc/geomap.htm

Geological Survey, 1998). Floodplain and terrace alluvial deposits are located along the streams that flow generally from west to southeast across the state (Branson and Johnson, 1979). Not all of the alluvial deposits are shown on Fig. 2.1.

Surface and Ground Water Resources. Two major streams, the Red River and Arkansas River and their tributaries, Cimarron River, the North Canadian and Canadian Rivers, and the Salt Fork of the Arkansas River, flow through a vast region in Southwestern Kansas, western Oklahoma and Northwestern Texas underlain by halite deposits of Permian age (Ward, 1961; Holdoway, 1978; Green et al., 1999) (Fig. 1, Appendix A). The Red River and the Arkansas River receive up to 8,000 tons of sodium chloride per day (Ward, 1961).

Ground water in Oklahoma is characterized by high variability in salt content on a local and regional scale (Table 2.1, Fig. 2.2). Extensive areas and/or small pockets of ground water high in sodium content can be found throughout the state (Knechtel, 1949; Warren, 1952; Davis, 1960; Mogg et al., 1960; Motts, 1963; Hart, 1978). In the Pahhandle and west central regions water is moderately hard with relatively low sodium content (SAR<13) (Marine and Schoff, 1962; Hart, 1978).

Climate. Oklahoma has a continental type climate with pronounced geographic ranges in temperature, precipitation, and annual lake evaporation (Fig. 2.3-2.5) as described by Gray and Galloway (1959) and Johnson and Duchon (1995). Oklahoma's location in the middle of the continent leads to hot summers with the climate sufficiently modified by moist air from the Gulf of Mexico resulting in large seasonal variations of precipitation (Johnson and Duchon, 1995). The vast open plains of the western two-thirds are dryer than the eastern third of the state. In the eastern section, rain showers are

TABLE 2.1

GROUND WATER IN OKLAHOMA*

Region&	Formation	Mineral content#
		Zone I
Panhandle	Ogallala	very hard but very low in sulfates and chlorides and TDS
North West	Cloud Chief	high in $CaSO_4$, cons $MgSO_4$ and $NaSO_4$
West Central	Marlow member	high in Ca, Mg and Na sulfates and NaCl
	Rush Spring member	Mg bicarb, Na and Mg sulfates, and NaCl
	Quatermaster	high in Ca and Mg bicarb, some Na sulfate, chloride and bicarb
	Blaine	high in $CaSO_4$, $MgSO_4$, cons Na_2SO_4 and NaCl
		Zone II
South West	Clear Fork Wichita	large amounts of Na chlorides, bicarbonates, and sulfates
	Arbuckle Limestone	high in sodium salts, low in Ca and Mg bicarbs
		Zone III
Central	Chickasha-Duncan	cons $MgSO_4$, $NaSO_4$ and NaCl, mod CaSO4
	Dog Creek, Flower Pot, and Vamoosa	locally high in $CaSO_4$, Na_2SO_4, $NaHCO_3$, and NaCl
	Wabaunsee	soft, locally high in $NaSO_4$ and cons Na bicarb and chloride
	Garber Sanstone	high in TDS, high $NaHCO_3$ and Na_2SO_4
	Wellington	cons Ca and Na sulfate, locally high in NaCl
	Hennessey, and Dog Creek	high in Ca, Mg and Na sulfates and NaCl
	Elgin sandstone	soft, locally high in NaCl
	Labette shale	high in Na_2CO_3 and NaCl

TABLE 2.1, cont'd

Region	Formation	Mineral content#
		Zone III, cont'd
Central	Francis formation	high in Na_2CO_3, Na_2SO_4 and NaCl
		Zone IV
South eastern and Southern	Woodbine	locally high in TDS and Na†
	Trinity sand	soft, high in Na_2CO_3
	Washita	hard water, locally high in Na†
		Zone V
East Central	McAlester	soft, high in NaHCO3
	Wewoka	soft, high in Na_2CO_3 and NaCl
	Boggy, and	
	Thurman sandstone	fair quality
		Zone VI
North East	Boone Limestone (VIa)	moderately soft
	Arbuckle Limestone (VIb)	locally highly mineralized
		Zone VII
Arbucle and Wichita Mountings	Arbuckle limestone	high in Ca and Mg bicarb, low in Na sulfate and chloride
		Zone VIII
Alluvial deposits (not shown on a map)		generally low in TDS

* - from Dott (1942) and Smith (1942)

& - see Fig. 2.2

- TDS = total dissolved solids, mod = moderate, cons = considerable, bicarb = bicarbonates

† - from Davis, 1960

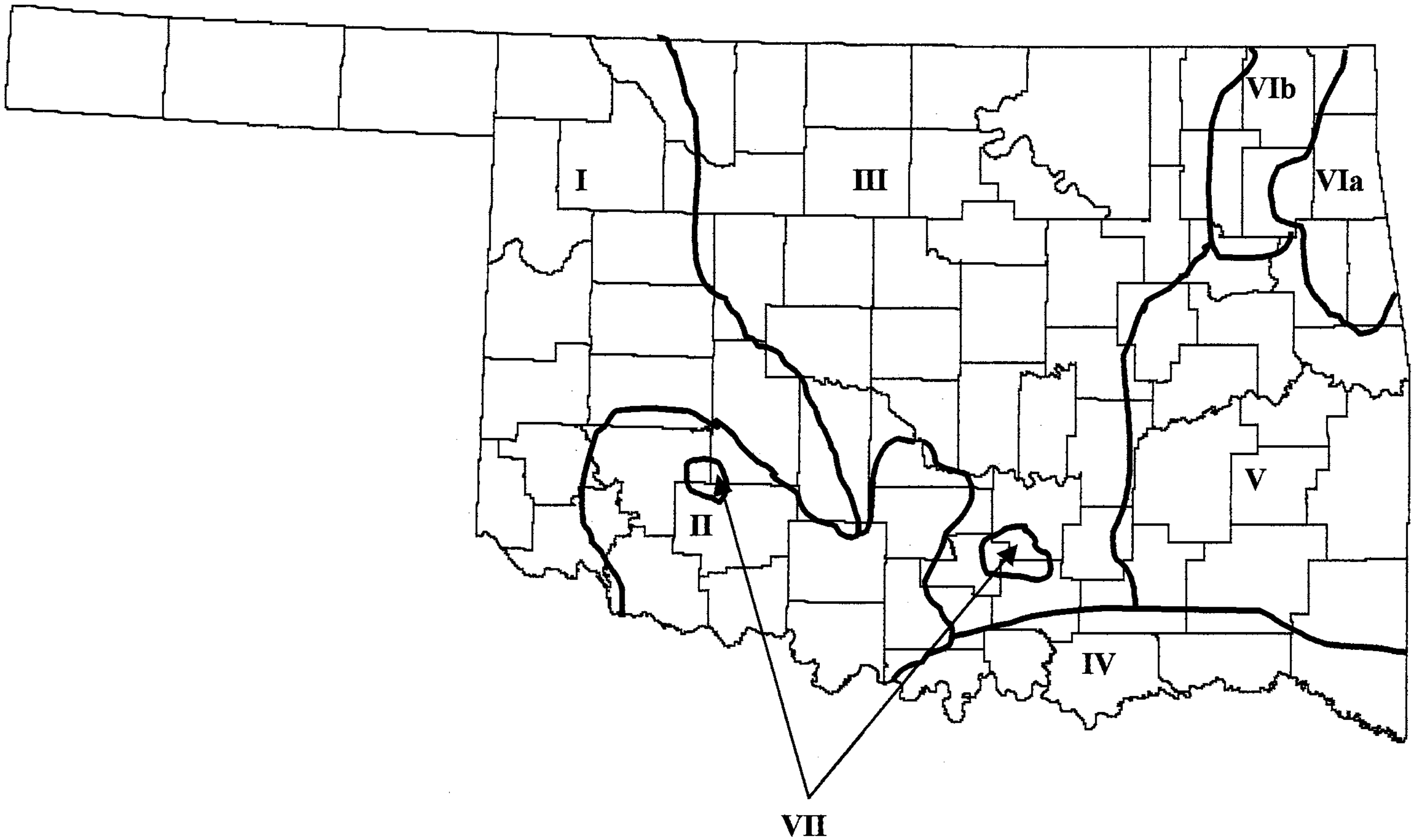

Fig. 2.2. Ground Water Zones of Oklahoma (see Table 2.1)

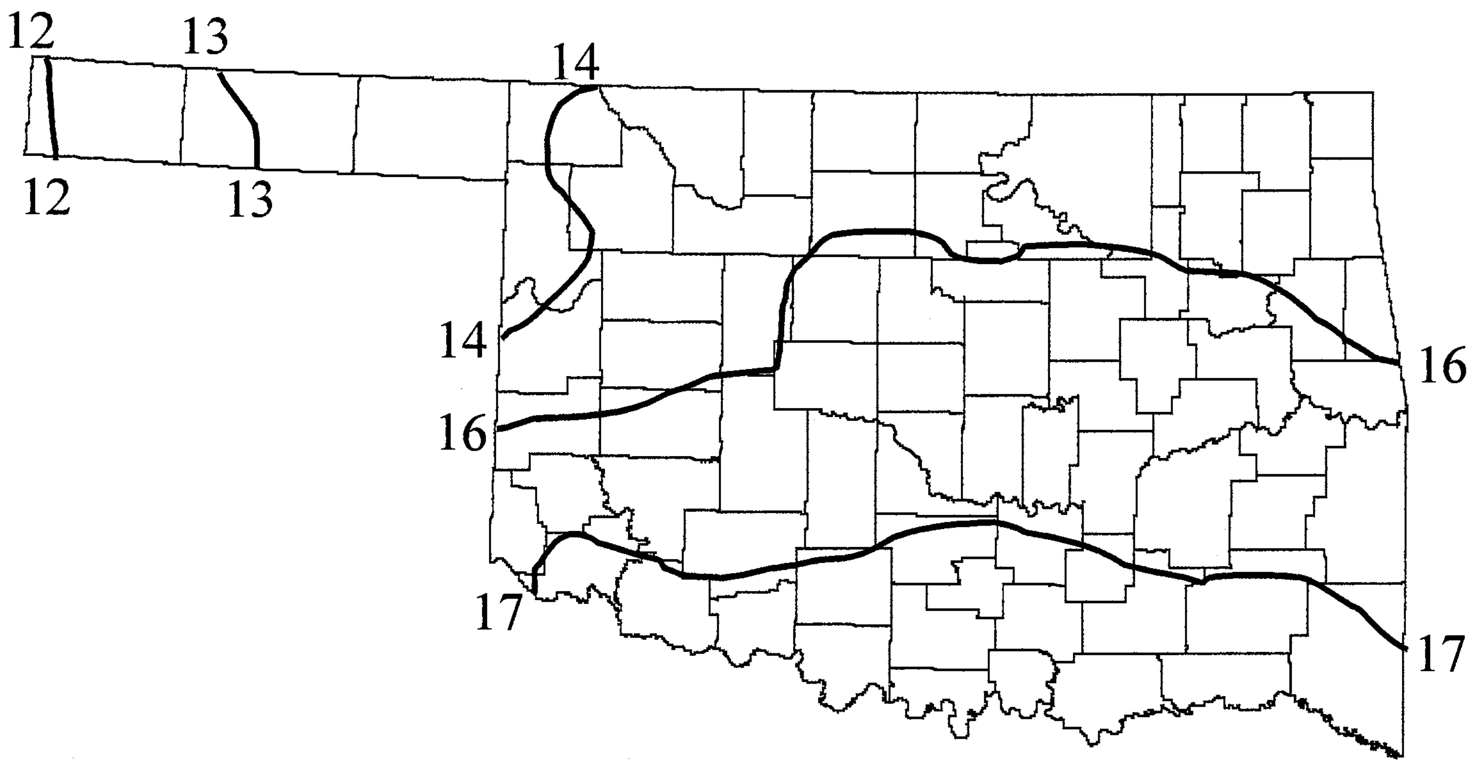

Fig. 2.3. Mean Annual Temperature in Oklahoma (C°).
Modified after Johnson and Duchon (1995)

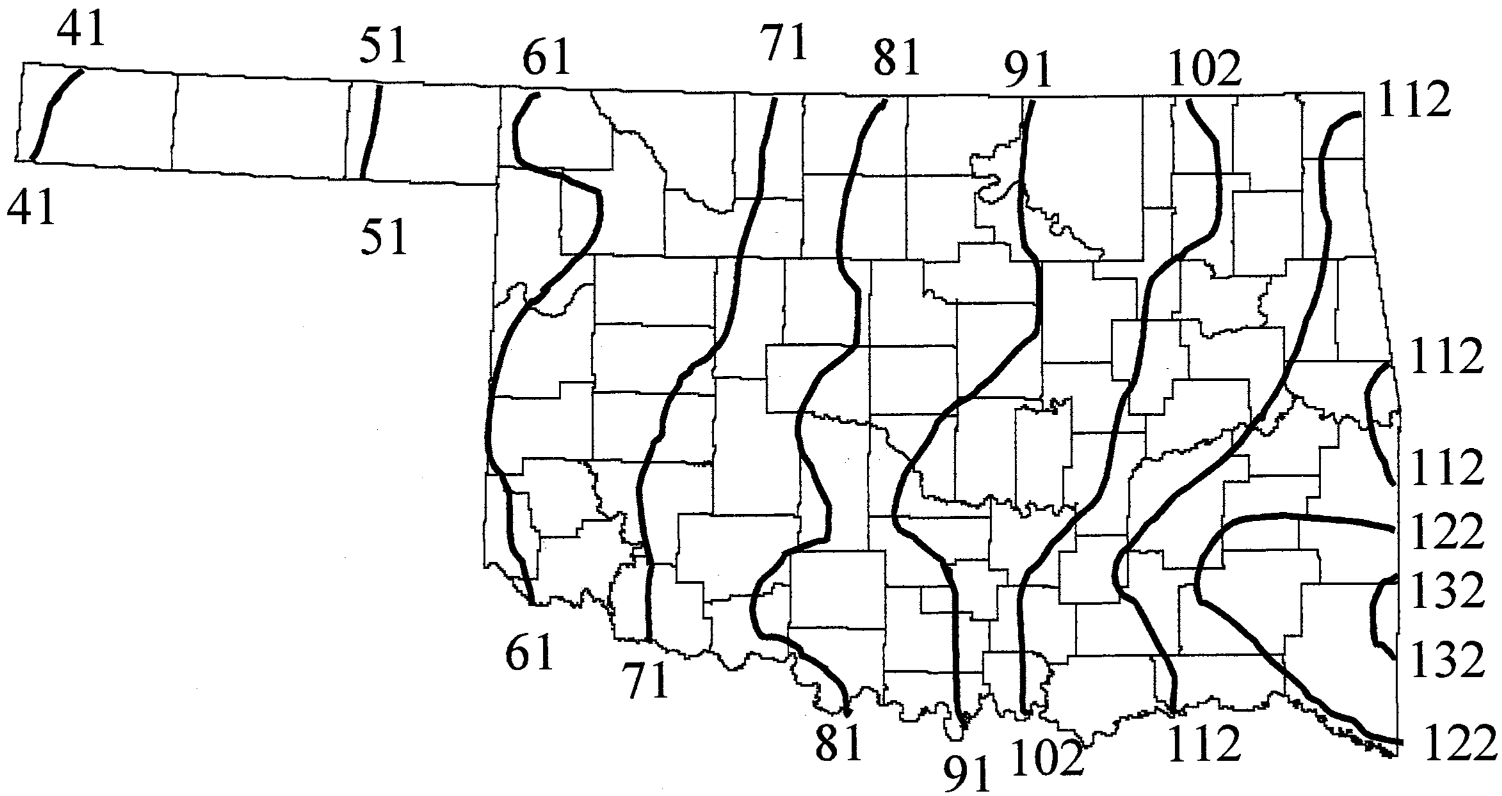

Fig. 2.4. Mean Annual Precipitation in Oklahoma (cm).
Modified after Johnson and Branson (1995)

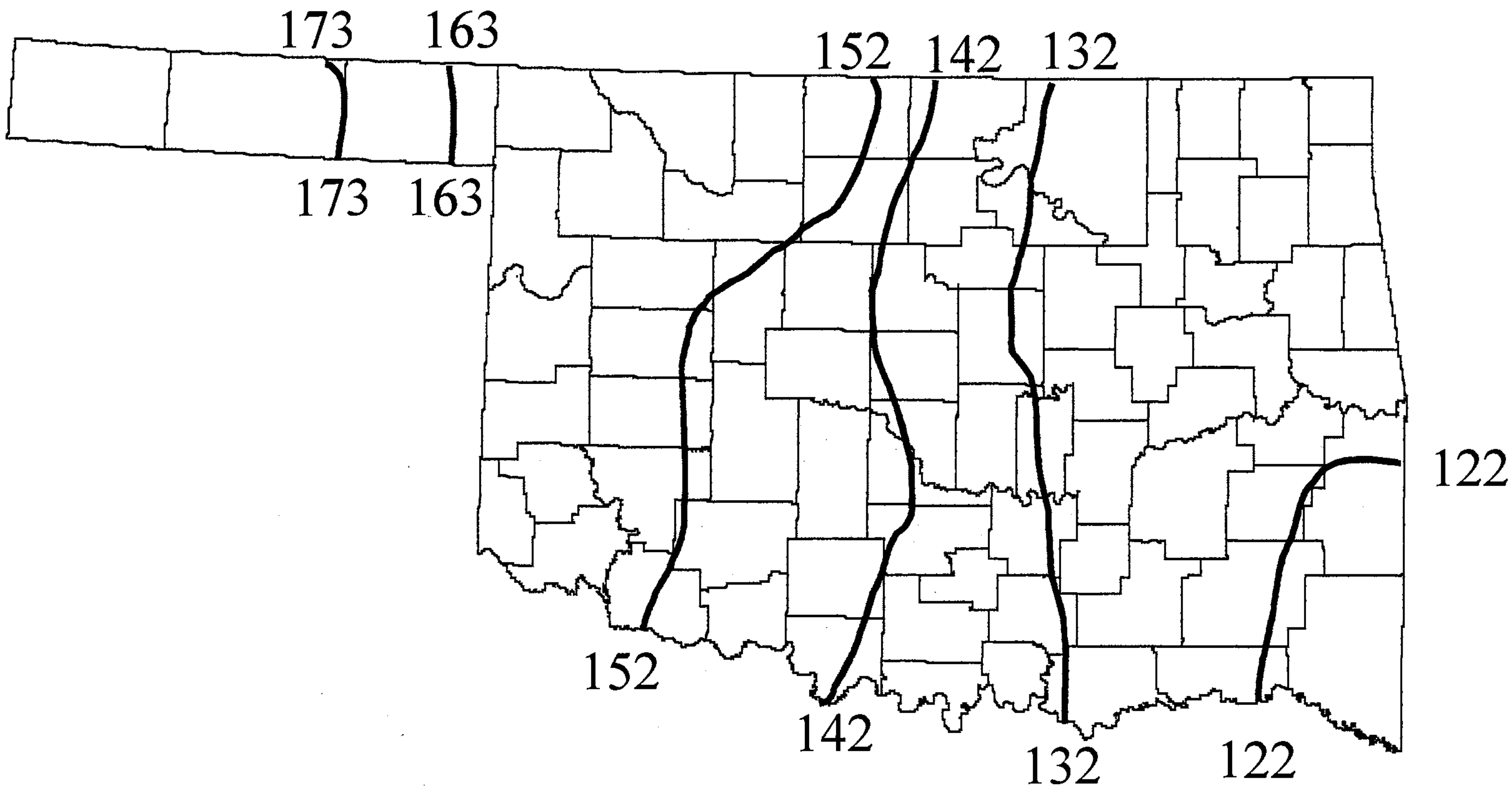

Fig. 2.5. Estimated Annual Lake Evaporation in Oklahoma
Modified after Johnson and Branson (1995)

more frequent, especially during late summer and early fall, because of the more humid atmosphere and the influence of the hilly, wooded terrain. Hot drying winds from the south and west sometimes occur during the summer months contributing to rapid evapotranspiration of soil moisture (Gray and Galloway, 1959).

Sodic Soils. Sodic soils in Oklahoma cover only about a 3% area of the whole state, but in some regions (southwest part of the state along Red River) they are quite extensive taking up to 36% of the area (Fig 2.6). Taxonomic classification of sodic soils found in Oklahoma is represented in Table 2.2.

Computer Generated Maps

ArcView/Geographic Information System software was used to produce sodic soil maps for all counties to aid in viewing sodium-affected soil distribution in Oklahoma. County 1:20,000-scale soil maps (USDA/NRCS county soil surveys) were digitized by GIS specialist M. Gregory at Oklahoma State University (resolution 200m X 200 m pixels). In ArcView each of the obtained images was superimposed on the stream and road network of the corresponding county to create interactive computer and hard copy soil maps. The Digital Atlas of Oklahoma (software, compiled by United States Geological Survey, 1997) was used as a source of geographic features. The exact geologic formation for each soil studied was determined using a 1:200, 000 - 1:300, 000 scale geologic maps of counties where soils were sampled (Oklahoma Highway Department, 1965; Oklahoma Highway Department, 1966; Oklahoma Highway Department, 1967; Oklahoma Highway Department, 1969a; Oklahoma Highway

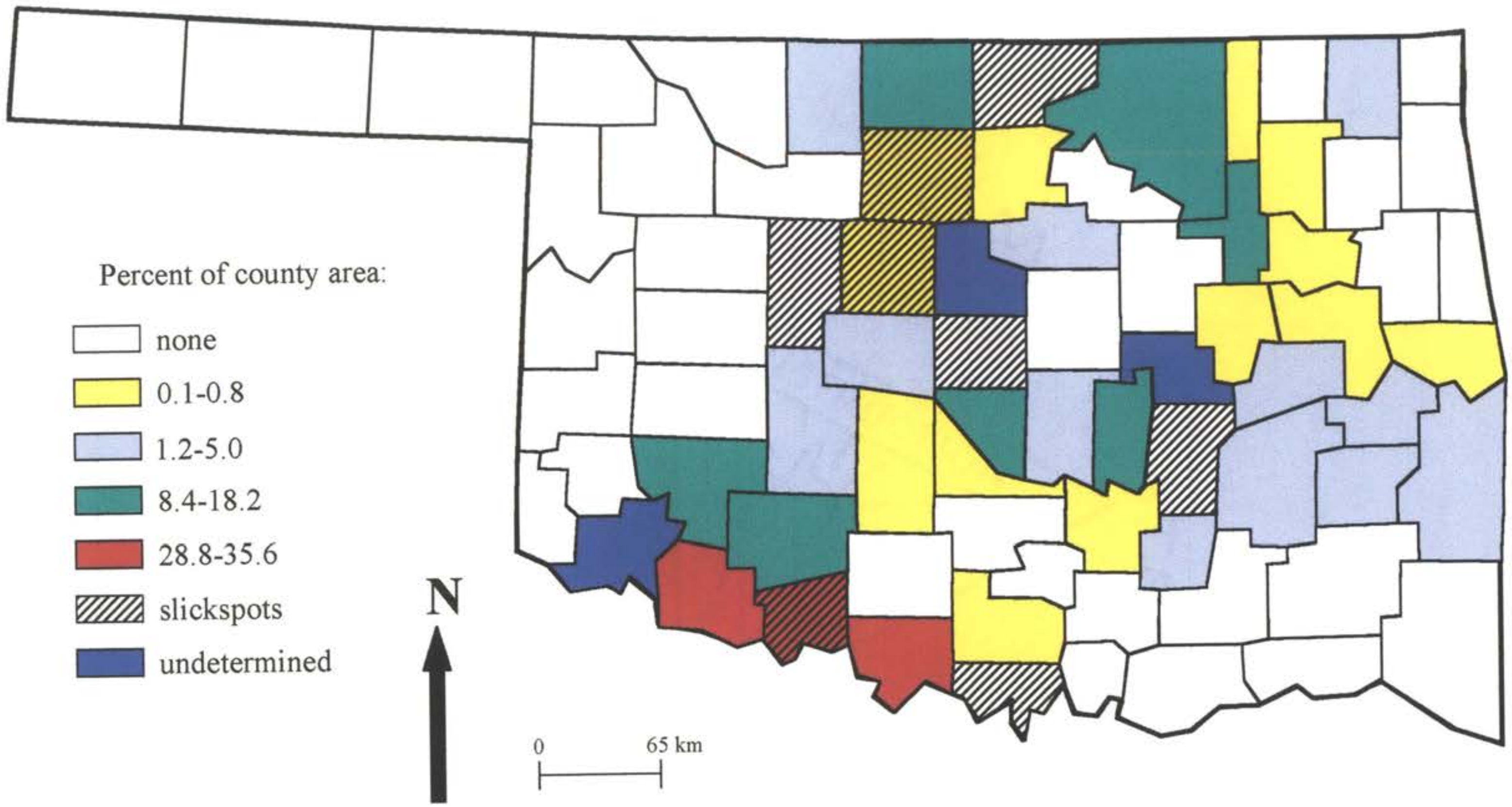

Fig. 2.6. Distribution of Sodic Soils in Oklahoma
Source: USDA/NRCS county soil surveys
Map compiled by Elena Jigoulina

TABLE 2.2

TAXONOMIC CLASSES OF SODIC SOILS IN OKLAHOMA*.

Soil Series	Taxonomic class	Source
Bonn	Fine-silty, mixed,superactive, thermic Glossic Natraqualfs	
Carytown	Fine, mixed, thermic Albic Natraqualfs	
Doolin	Fine, smectitic, thermic Typic Natrustolls	
	Fine, montmorillonitic, thermic Typic Natrustolls	Henley et al. (1987)
Drummond	Fine, mixed, superactive, thermic Mollic Natrustalfs	
	Fine, mixed, thermic Mollic Natrustalfs	Fisher and Swafford (1976), Williams et al. (1985)
Dwight	Fine, smectitic, mesic Typic Natrustolls	
	Fine, montmorillonitic, mesic Typic Natrustolls	Boutlier et al. (1979)
	Fine, mixed, mesic Typic Natrustalfs	Shingleton, L.C. (1971)
	Fine, mixed, thermic Typic Natrustolls	Sparwasser et al. (1968)
Foard	Fine, smectitic, thermic Vertic Natrustolls	
	Fine, montmorillonitic, thermic Typic Natrustolls	Lamar (1979)
Healdton	Fine, mixed, thermic Vertic Natraqualfs	
	Fine, smectitic, thermic Typic Natraqualfs	Moebius and Maxwell (1979)
Hinkle	Fine, smectitic, thermic Vertic Natrustalfs	
	Fine, montmorillonitic, thermic Mollic Natrustalfs	Lamar (1979)
Huska	Fine, mixed, superactive, thermic Mollic Natrustalfs	
	Fine, mixed, thermic Mollic Natrustalfs	Henley et al. (1987)
Lafe	Fine-silty, mixed, active, thermic Glossic Natrudalf	
	Fine-silty, mixed, thermic Glossaquic Natraqualf	Abernathy (1970)
Oscar	Fine-silty, mixed, superactive, thermic Typic Natrustalf	
	Fine-silty, mixed, thermic Typic Natrustalf	Lamar and Rhodes (1974) Mobley and Ringwald (1979)
Pawhuska	Fine, mixed, superactive, thermic Mollic Natrustalf	
	Fine, mixed, thermic Mollic Natrustalf	Moebius and Sparwasser (1979)
Seminole	Fine, mixed, thermic Typic Natrustoll	
Wakita	Fine-silty, mixed, active, thermic Leptic Natrustoll	
Wing	Fine, mixed, thermic Aquic Natrustalf	
Wister	Fine, mixed, thermic Vertic Natrudalf	
	Fine, mixed, thermic Albaquic Hapludalf	Abernathy et al. (1983)

* - as classified by USDA/NRCS, http://www.statlab.iastate.edu/soils/osd/

Department, 1969b; Oklahoma Highway Department, 1969c; Oklahoma Highway Department, 1970).

A map of the state was also produced in ArcView based on updated interchange files provided by GIS Section of local USDA/NRCS. This map was used to determine sodic soil distribution patterns in relation to regional geology and climatic characteristics.

Soil Sampling and Characterization

The study was conducted in 18 counties throughout Oklahoma in July-August, 1997. Twenty-three soil profiles of 15 sodic soil series were selected as representatives of Oklahoma sodic soils after preliminary study of soils at 44 sites in 28 counties in different regions of Oklahoma. In addition to sodic soils, the soil of the Bosville Series located in the southeast part of the state was selected to represent dispersive soils based on preliminary study of 7 sites in 3 southeastern counties (Choctaw, Atoka, and Pushmataha). The Bosville soil series is classified by USDA/NRCS as fine, mixed, thermic Albaquic Paleudalf. Sampling locations and soil series studied are shown on Fig. 2.7. Soil mapping units sampled and site legal descriptions are represented in Table 2.3.

A T-shaped pit 2 meters deep was excavated at each sampling site. Soils were examined and described in the field by standard techniques (Soil Survey Division Staff, 1993). A horizon was considered natric (with designation Bn) if it had prismatic structure and siltans or clay and organic coatings along ped faces. Moist soil color was determined by using Munsell Soil Color Charts (GretagMcbeth, 1994). A total of 152 genetic horizons were sampled. Each sample was air-dried and passed through a 2mm

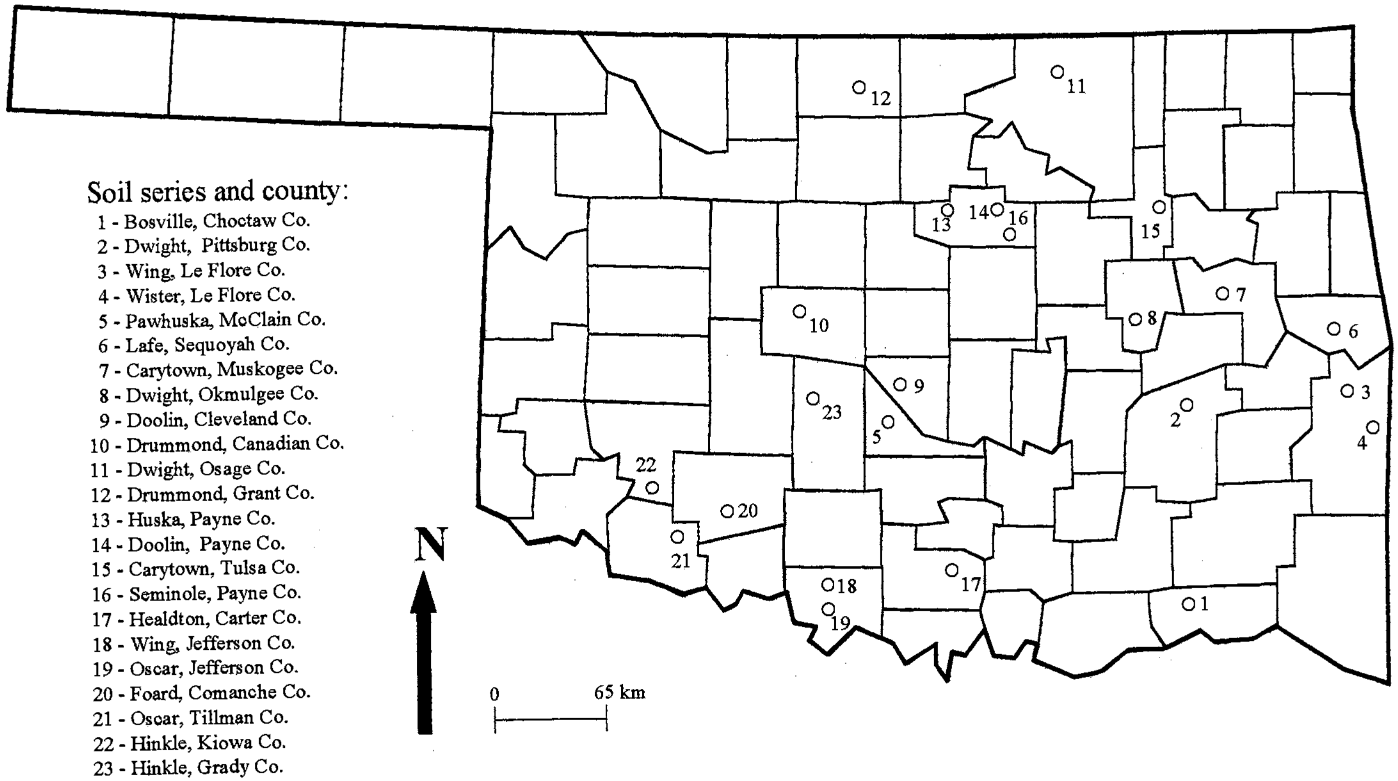

Fig. 2.7. Sampling Locations of Sodic Soils Studied

TABLE 2.3

SITE DESCRIPTIONS OF SOILS STUDIED

Site No.	Soil mapping unit	County	Legal description	Associated soil series
1	Bosville sandy loam, 4-8% slopes	Choctaw	SE1/4 NW1/4 Sec.20 T6SR15E	Muskogee, Bernow
2	Parsons-Dwight complex, 1-3% slopes, eroded	Pittsburgh	NW1/4 SE1/4 Sec.22 T8NR14E	Dennis, Choteau
3	Wing silt loam, 0-2% slopes	Le Flore	SW1/4 SW1/4 Sec.16 T9N R24E	Wister, Stigler
4	Wister silt loam, 0-1% slopes	Le Flore	SW1/4 NE1/4 Sec.34 T8NR26E	Wing
5	Bethany-Pawhuska complex, 0-3% slopes	McClain	NE1/4 SE1/4 Sec.1 T7NR3W	Bethany, Kirkland, Port, Renfrow, Grant
6	Lafe soils	Sequoyah	NE1/4 NE1/4 Sec. 1 T11NR24E Ennis	Stigler, Rosébloom,
7	Parsons-Carytown silt loam 0-1% slopes	Muskogee	SW1/4 NW1/4 Sec.4 T13NR18E	Taloka, Dennis Verdigris
8	Dwight-Parsons silt loams, 0-1% slopes	Okmulgee	SW1/4 NW1/4 Sec.20 T12NR12E	Okemah, Dennis, Woodson,

TABLE 2.3, cont'd.

Site No.	Soil mapping unit	County	Legal description	Associated soil series
9	Doolin-Pawhuska complex	Cleveland	NE1/4 NE1/4 Sec33. T10NR3W	Grainola, Weswood
10	Brewer-Drummond complex	Canadian	NW1/4 SW 1/4 Sec.19 T14NR9W	Dale, Canadian, Shellabarger
11	Apperson-Dwight complex, 0-3% slopes	Osage	NW1/4 NW1/4 Sec.28 T29NR7E	Foraker, Shidler, Parsons, Carytown Summit,
12	McClain-Drummond silt loams, flooded	Grant	NE1/4 NW1/4 Sec.18 T26NR4W	McClain, Oscar, Grant, rarely Tabler, Dale
13	Zaneis-Huska complex, 1-5% slopes	Payne	NE1/4 NW1/4 Sec.10 T19NR2E	Renfrow, Grainola, Ashport
14	Doolin silt loam 0-2% slopes	Payne	N1/2 NE1/4 Sec.2 T19NR4E	Zaneis, Huska, Coyle, Grainola, Mulhall Lucien,
15	Okemah-Parsons-Carytown 0-1% slopes	Tulsa	E1/2 SE1/4 Sec.3 T19NR14E	Dennis, Radley, complex, Carytown, Apperson, slickspots
16	Seminole loam, 0-2% slopes	Payne	S1/2 SE1/4 Sec.4 T17NR6E	Chickasha, Steedman, Gowen

TABLE 2.3, cont'd.

Site No.	Soil mapping unit	County	Legal description	Associated soil series
17	Healdton silt loam	Carter	NE1/4 SW1/4 Sec.35 T3SR2E Bunyan, Pulaski,	Watonga, Konawa,
18	Zaneis-Wing complex, 0-3% slopes	Jefferson	NW1/4 SW1/4 Sec.8 T4SR6W	Zaneis, Lucien, Vernon Kirkland, Port, Oscar
19	Port-Oscar complex	Jefferson	SE1/4 SW1/4 Sec.26 T4SR7W	Zaneis, Wing, Lucien Vernon
20	Foard silt loam, 0-1% slopes	Comanche	NE1/4 SE1/4 Sec.22 T1NR12W	Tillman, Vernon
21	Asa-Oscar complex	Tillman	SW1/4 SW1/4 Sec.3 T1SR15W	Indiahoma, Vernon Clairemont, slickspots
22	St-Paul-Hinkle complex, 0-1% slopes	Kiowa	NE1/4 SE1/4 Sec.23 T2NR17W	Carey, Clairemont, Port Mangum, Hollister, slickspots
23	Renfrow-Hinkle complex, 1-3 % slopes	Grady	NE1/4 NW1/4 Sec.19 T8NR7W	Renfrow, Grant, Port, Kirkland

sieve. Soil characterization was performed in the Department of Plant and Soil Sciences at Oklahoma State University. The particle size distribution was determined using the pipette method following removal of salts and organic matter (Gee and Bauder, 1986; USDA, NRCS, NSSC, 1996a). Soil bulk density was measured on saran-coated clods (Blake and Hartge, 1986; USDA, NRCS, NSSC, 1996b). Organic matter content was identified by titration following digestion with an acidified dichromate (Yeomans and Bremner, 1988). Saturation extracts from each horizon and ground water samples for some sites (where present) were analyzed for pH, electrical conductivity (EC), and major cations and anions. The reaction (pH) was measured with a calibrated combination electrode/digital pH meter (McLean, 1982; USDA, NRCS, NSSC, 1996c). A conductivity bridge was employed to measure EC (U.S. Salinity Laboratory Staff, 1954; USDA, NRCS, NSSC, 1996d). Soluble calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) were determined by atomic absorption spectophotometry (U.S. Salinity Laboratory Staff, 1954; USDA, NRCS, NSSC, 1996e). Carbonates and bicarbonates were analyzed by titration (U.S. Salinity Laboratory Staff, 1954; USDA, NRCS, NSSC, 1996f). Chloride, sulfate, nitrate, fluoride, and bromide were determined by ion chromatography (U.S. Salinity Laboratory Staff, 1954; USDA, NRCS, NSSC, 1996g). The SAR was calculated from soluble Na, Mg, and Ca concentration using the following equation (U.S. Salinity Laboratory Staff, 1954; USDA, NRCS, NSSC, 1996h):

$$SAR = Na / ((Ca + Mg)/2)^{1/2}$$

Cation exchange capacity (CEC) was determined on selected horizons using the method for soils containing soluble salts and carbonates (Sumner and Miller, 1996). Exchangeable sodium percentages (ESP) for these horizons were calculated from extractable sodium and CEC values (U.S. Salinity Laboratory Staff, 1954; USDA, NRCS, NSSC, 1996i). Extractable acidity (USDA, NRCS, NSSC, 1996k) was determined by leaching soil with barium chloride-thriethanolamine ($BaCl_2$-TEA) solution buffered at pH=8.2 using a mechanical automatic extractor (Holmgren, 1977) followed by HCl titration (Peech et al, 1947). Data on CEC, ESP, and exchangeable acidity of soil profiles 5, 7, 9, 20, and 22 were taken from National Soil Survey Center (http://vmhost.cdp.state.ne.us/~nslsoil/STATE.HTML). X-ray diffraction techniques were used to identify clay mineralogy of selected profiles and horizons (Whittig, and Allardice, 1986). The Oklahoma Department of Transportation Testing Laboratory provided dispersion characteristics of soils tested with the double hydrometer (ASTM Standard D4221, 1990), pinhole (ASTM Standard D4647, 1990), and crumb (Emerson, 1954) methods. Double hydrometer data were used in the analysis.

The presence of redoximorphic features was identified by the color. Redoximorphic depletions were determined by presence of gleic colors or colors with a high value (≥4) and low chroma (≤2) (Soil Survey Staff, 1999).

Classifying of sodic soils was conducted using standard techniques (Soil Survey Staff, 1999) with the assistance of the state NRCS, USDA, Stillwater, Oklahoma Office.

To study climate effect, soils were divided into groups based on soil moisture regime (Soil Survey Quality Assurance Staff, 1994) and climate classification suggested by Thorntwaite (1931), the latter is based on the Precipitation –Evaporation (P-E) index calculated as follows:

$$\text{P-I index} = \sum_{n=1}^{12} 115 * (P/(T-10))_n^{\frac{9}{10}},$$

where P – is precipitation in inches and T – is temperature in F°. Precipitation and temperature data for ten consecutive years where taken from 15 Oklahoma weather stations (National Oceanic and Atmospheric Administration, 1988-1999) located close to the sites where soils were sampled. Average P-E index and the range for each station are presented in Table 2.4.

Results and Discussion

Sodic soils in Oklahoma are located in areas with a range of mean annual temperature of 14 C° to 16 C°, a mean annual precipitation of 71 to 122 cm, and an estimated annual lake evaporation of 122-163 cm. Areas where precipitation exceeds evaporation do not contain sodic soils. To reveal the effect of climate on sodic soil variability in Oklahoma, soils were grouped based on soil moisture regimes (Soil Survey Quality Assurance Staff, 1994). Further division of subgroups was made using climate classification proposed by Thorntwaite (1931) and based on the P-E Index:

Humidity Province	P-E Index
Wet	128 and above
Humid	64 to 127
Sub-humid	32 to 63

Table 2.5 shows the resulting soil groups. There is a gradual change in the mean and range values of the P-E index. Other soil forming factors (parent material, topography,

TABLE 2.4

P-E INDICES FOR WEATHER STATIONS IN OKLAHOMA FOR REGIONS STUDIED

Station, County	Soil Series (Site number)	Average P-E Index	P-E Index Range
Warika, Jefferson	Wing (18), Oscar (19)	54	41-72
Frederick, Tillman	Oscar (21)	57	40-70
Lawton, Comanche	Foard (20)	59	42-78
Jefferson, Grant	Drummond (12)	62	42-87
El Rino, Canadian	Drummond (10)	63	39-74
Wichita Mnt Wl Ref#, Kiowa	Hinkle (22)	66	52-81
Blanchard, McClain	Pawhuska (5)) Doolin (9)	67	47-87
Chickasha Exp, Grady	Hinkle (23)	67	59-81
Healdton, Carter	Healdton	70	51-98
Stillwater, Payne	Doolin (14)	71	58-90
Tulsa Int'l AP*, Tulsa	Carytown (15)	74	58-90
Cushing, Payne	Seminole (16)	75	59-87
Muskogee, Muskogee	Carytown (7)	86	67-112
Okmulgee Water Works, Okmulgee	Dwight (8)	89	74-108
Pawhuska, Osage	Dwight (11)	90	68-104
Eufaula, McIntosh	Dwight (2)	92	69-129
Hugo, Choctaw	Bosville (1)	95	67-116
Sallisaw, Sequoyah	Lafe (6)	97	72-152
Poteau Water Works, Le Flore	Wing (3), Wister (4)	99	74-144

- Wichita Mountain Wildlife Refuge
* - Tulsa International Airport

TABLE 2.5.

CLIMATIC GROUPS FOR SOILS STUDIED

Soil Series (Site number)	Group	Description
Bosville (2) Dwight (2) Wing (3) Wister (4) Lafe (6)	Udic humid-wet	Udic moisture regime Average P-E Index of 92-99 P-E index range 67-152
Carytown (7), Dwight (8)	Udic humid	Udic moisture regime Average P-E Index of 86-89 P-E Index range 67-112
Carytown (15)	Udic subhumid-humid	Udic moisture regime Average P-E Index of 74 P-E range 58-90
Dwight (11)	Udic ustic humid	Udic ustic moisture regime Average P-E Index 90 P-E Index range 68-104
Pawhuska (5) Doolin (9) Doolin (14) Seminole (16) Healdton (17) Hinkle (23)	Udic ustic subhumid-humid	Udic ustic moisture regime Average P-E Index > 63
Drummond (10), Drummond (12) Wing (18) Oscar (19)	Udic ustic subhumid	Udic ustic moisture regime Average P-I index ≤ 63
Foard (20) Oscar (21) Hinkle (22)	Typic ustic subhumid-humid	Typic ustic moisture regime

vegetation, and time) contribute significantly to sodic soil variability and are discussed in corresponding sections.

Soil depths and horizon designations of soils studied are presented in Table 2.6. Soil profile sampled as Huska soil series in Zaneis-Huska complex (Site 13) did not meet the chemical criteria for sodic soils (SAR $\geq$ 13) and was not included in the analysis.

<u>Effect of Time on Sodic Soil Variability</u>

The length of time since deposition of the material, the exposure of the material at the surface, or formation of the slope to which the soil relates influences soil formation (Birkeland, 1999). Alhough time is a passive factor (Daniels and Hammer, 1992; Birkeland, 1999), most soil forming processes are so slow that their effect on the soil is time dependent. Time affects variability of sodic soils. A saline soil, with time, transforms into a Solonetz, which in turn, with time, becomes a Solod (de Sigmond, 1926; Gedroitz, 1927; Kellog, 1934). Permanent changes in soil properties usually occur in a period longer than a human life span, which makes it impossible to observe actual changes that are time dependent. Also, it is impossible to differentiate the effect of time from the effect of other factors. In periods of time when parent material, climate, vegetation, and topography may be considered constant, the effect of time on the soil development is expressed as a soil chronofunction (Jenny, 1941) and is possible to study if the time of the original sampling is available. For soils studied, there was no starting point from which to compare the data collected. Our vision of time as it effects sodic soil formation in this study can only be hypothetic.

TABLE 2.6

DEPTHS AND HORIZONS OF SOILS STUDIED

Soil Series	Solum depth, cm	Horizons	
		Udic	
		Humid-wet	
Bosville (1)	168	Ap, E, Bt1, Bt2, Bty3, Bty4, BC	
Dwight (2)	140	Ap, Bn1, Bn2, Bt3, Bt4, BC	
Wing (3)	115	Ap, Bt1, Bty2, 2Btk3, 2BCk	20
Wister (4)	105	Ap, E, Bt1, Bt2, Bt3, Cr	78+
Lafe (6)	95	Ap, Btn1, Bty2, Btky3, BCk, 2Cr, 2Cr2	
		Humid-subhumid	
Carytown (7)	193+	Ap, E, Btn1, Bt2, Bty3, Bty4, Bty5	
Dwight (8)	152	Ap, Bn1, Btk2, Btk3, BCk	
		Subhumid	
Carytown (15)	172	A, Btn1, Btn2, Btny3, Btn4, Btnk5, 2Cr	
		Udic ustic	
		Humid	
Dwight (11)	95	A, Btn1, Btn2, Bt3, C, 2Cr1, 2Cr2	
		Humid subhumid	
Pawhuska (5)	150	Ap, Bn1, Bty2, Btk3, Bt4, BC	120-210
Doolin (9)	160	Ap1, Ap2, Btn1, Btk2, Btky3, Btk4, 2BCk	
Doolin (14)	166	A, Btn, Btn2, Btkn3, Btnyq4, Btnq5, 2R	
Seminole (16)	137	A, BAn, Btn1, Btn2, Btnky3, 2Cr1, 2Cr2	
Healdton (17)	202	Ap, Btn1, Btn2, Btk3, Btk4, Akssb, Btkss1	
Hinkle (23)	74	Ap, Btnss1, Btk2, Ck1, Cr2	
		Subhumid	
Drummond (10)	164+	Ap, Btk1, Btss2, Btss3, 2Bt4	
Drummond (12)	148+	Ap1, Ap2, A1,b; Bty1,b; Btk2,b; Btk3,b	
Wing (18)	97	Ap1, Ap2, Btn1, Btn2, Btkn3, BCkg, Cg, Cr	
Oscar (19)	200+	Ap, Btnky1, Btnky2, Btn3, Btc4, BC	
		Typic ustic	
Foard (20)	169	Ap, Btn1, Btnky2, Btnky3, Btnky4, BC, 2Ck	
Oscar (21)	144	Ap, Btkyn1, Btkyn2, Btkn3, Btkn4, Btkn5,	
Hinkle (22)	200	Ap, Btkn1, Btkyn2, Btkn3, Btkn4, Btkn5, BCk	

A hypothetical model followed in this study suggests that most areas in eastern Oklahoma probably had sodic soils more widespread in the past than today. Under humid climate (P-E index in a range of 67-127) these sodic soils were retained only in topographic lows where shallow water table and/or impermeable bedrock slowed down the leaching process (Fig. 2.8). In areas with lower P-E indexes (in a range 41 to 90) sodium and salts are retained close to the surface resulting in wide distribution of sodic and saline-sodic soils. Sodic soils of terraces and floodplains were probably formed as a more or less uniform sheet of saline-sodic soils along major rivers and later with improved drainage (along small drainage ways carrying water to these major streams) transformed into sodic as soluble salts were leached out (Fig. 2.9). Modern distribution of sodic soils in some areas supports this assumption (Fig. 2, 3, Appendix A).

Variability in sodic soils is affected by time in a way that there is a delay between soil chemistry changes and soil structure response, which leads to existence of soils with high SAR (more than 13) and blocky structure or soils with low SAR (less than 13) and prismatic or columnar structure.

Effect of Parent Material on Sodic Soil Distribution and Properties

Soils studied in this project were formed in alluvium of Quaternary age overlying bedrock material of Pennsylvanian, Permian, or Cretaceous age (Table 2.7). Several soils were formed in only residuum: shale (sites 4, 8, 11), sandstone (site 18), or siltstone (site 23). Distribution of sodic soils in Oklahoma by series as suggested by NRCS/USDA is shown on Fig. 2.10. The presence of sodic soils in alluvial deposits in the western part of

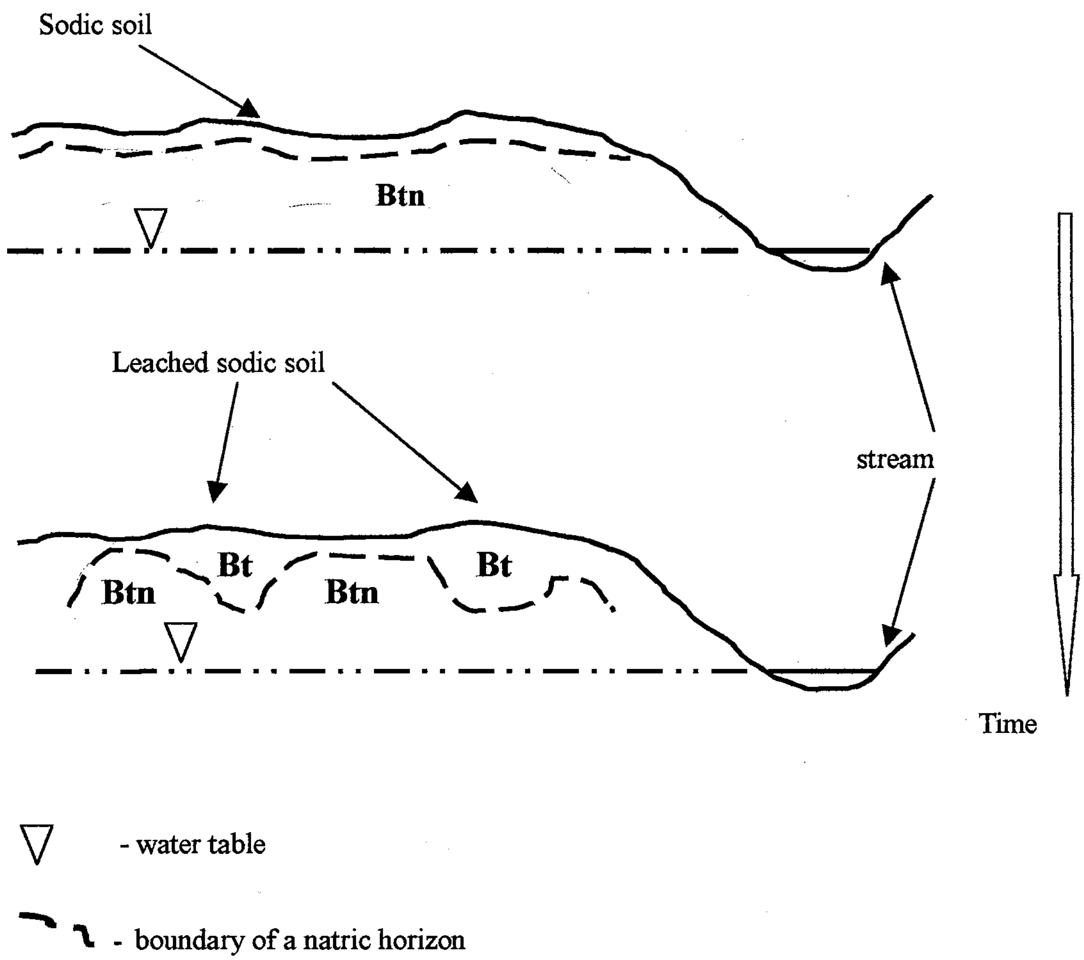

Fig. 2.8. Time-Dependent Sodic Soil Spatial Variability

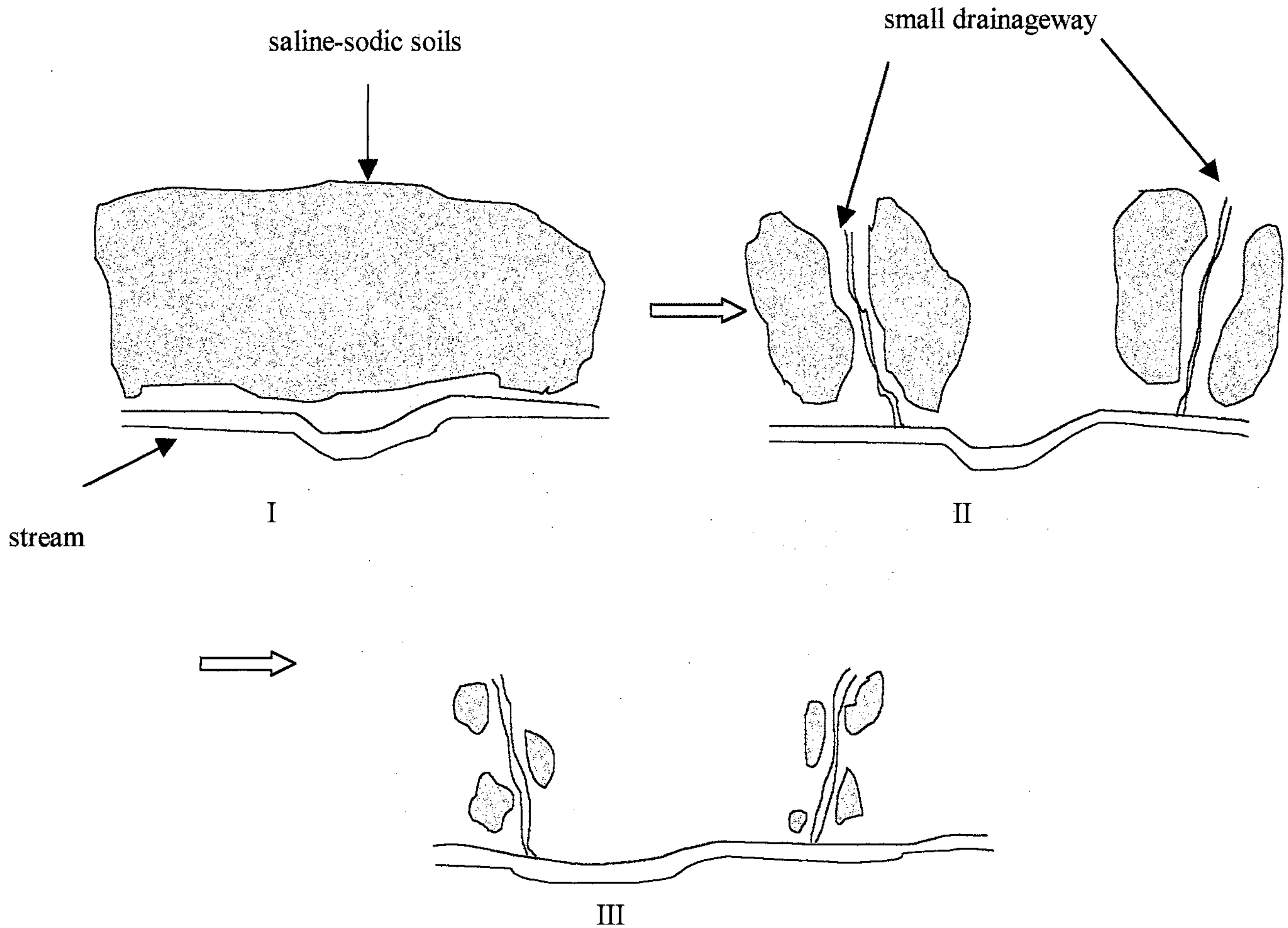

Fig. 2.9. Development of Sodic Soils along the Streams with Time
(I – initial stage, II - intermediate stage, III – final stage)

TABLE 2.7

PARENT AND BEDROCK MATERIAL UNDERLYING SOIL MAPPING UNITS UNDER STUDY

Soil Series (site number)	Parent material*			Underlying bedrock#		
	Formation	texture	color	formation	texture	color
Bosville, (1)	terrace deposits, Q	clay loam	brownish yellow	Washita unit (Cr)	shaly clays¶	blue to black¶
Dwight (2)	terrace deposits, Q	silty clay	gray	Thurman unit Pn	sst with some shale¶	brown to tan
Wing (3)	terrace deposits, Q	silty clay loam&	reddish yellow/gray&	McAlester unit Pn	shale¶	dark blue¶
Wister, (4)	McAlester unit, Pn¶	shale	olive	McAlester unit	shale¶	dark blue
Pawhuska, (5)	terrace deposits, Qts¶	silty clay red	yellowish	Hennessey unit Pe	shale and mudstone	red
Lafe soils (6)	terrace deposits, Q	clay loam	reddish yellow/gray	McAlester unit (Pn)	shale	dark blue¶
Carytown (7)	terrace deposits, Q	(clay loam)	(brownish yellow)	Boggy unit Pn	shale, sst siltstone	dark
Dwight (8)	Wewoka unit, Pn¶	clay loam	brown	Wewoka	clayey to silty shale	gray to black
Doolin (9)	terrace deposits, Qts¶	silty clay&	dark red&	Hennessey unit Pe	clay shale and mudstone	red

TABLE 2.7, cont'd

Soil Series (site number)	Parent material*			Underlying bedrock#		
	Formation	texture	color	formation	texture	color
Drummond (10)	alluvium Qas¶	(clay)	(grayish brown)	Dog Creek unit Pe	shale with gyp beds	orange to dark red
Dwight (11)	Red Eagle Limestone, Pn¶	shale	gray	Red Eagle, Pn	limestone with shale	gray
Drummond (12)	alluvium Qas¶	(silty clay loam)	(reddish brown)	Garber unit Pe	clay/sandy shales and sst	red
Doolin (14)	terrace deposits, Q	(silty clay loam)	(brown)	Wellington-Admire unit, Pe	shale with sandstone lenses	red
Carytown (15)	terrace deposits, Q	(silty clay loam)¶	(yellowish brown)	Labette shale Pn	calcareous shale	gray
Seminole (16)	terrace deposits, Q	(silty clay loam)	(brown)	Vanoss and Ada Pn	sandstone	
Healdton (17)	alluvium Qas	(silty clay loam)	(brown)	Hoxbar unit Pn	shale	gray
Wing (18)	Addington Unit, Pe¶†	sst		Addington unit Pe†	sst, shale,and mudstone	red-brown
Oscar (19)	alluvium Q	loam	reddish brown	Oscar unit Pe†	shale,and cngl	maroon to gray

TABLE 2.7, cont'd

Soil Series (site number)	Parent material*			Underlying bedrock#		
	Formation	texture	color	formation	texture	color
Foard (20)	terrace deposits, Q	silty clay	dusky red	Hennessey unit, Pe	clay shales and mudstone	reddish brown
Oscar (21)	alluvium Q	loam	pale brown	Addington unit, Pe†	sst, shale and mudstone	red-brown
Hinkle(22)	terrace deposits, Q	clay loam	dark red	Addington unit, Pe†	sst, shale and mudstone	red-brown
Hinkle (23)	Dog Creek-Blaine subunit Pe¶	siltstone	red	Dog creek-Blaine subunit, Pe	shales with gypsiferous sst	dark red

*- field data for BC and C-horizons, Q – terrace deposits not mapped on 1:200,000 scale map, texture and color for BC or C horizons, in parenthesis texture and color for the lowest horizon, sst – sandstone
-data from Oklahoma Highway Department, 1965-1970; Pn – Pennsylvanian, Pe-Permian, Cr-Cretaceous; Qts-Quaternary terrace deposits, Qas – quaternary alluvial deposits; sst – sandstone, gyp – gypsum, cngl - conglomerate
& - second parent material data
¶ – formation name from Highway Department, 1965-1970
† - Wichita Formation in Miser, 1954

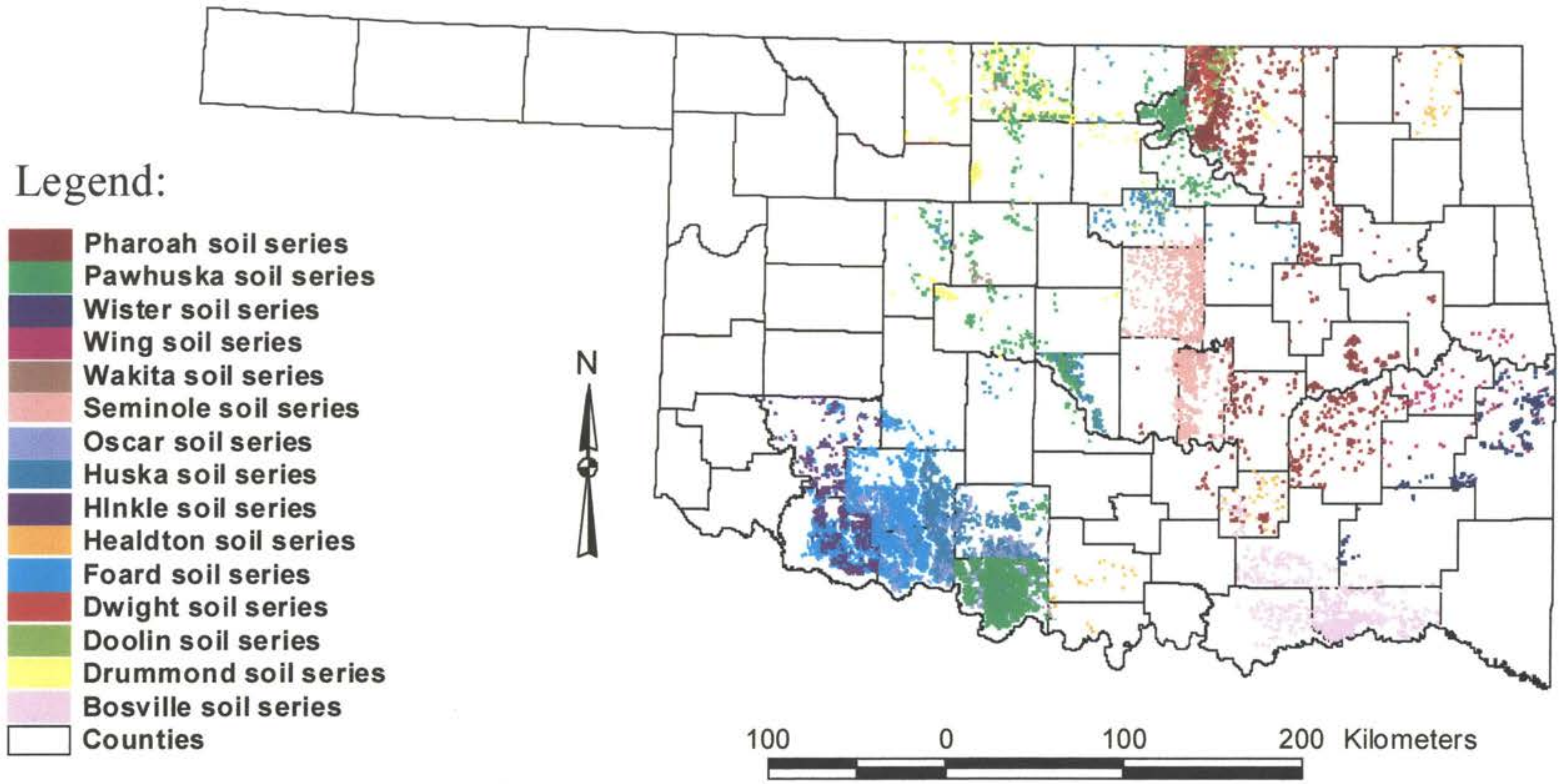

Fig. 2.10. Distribution of Sodic Soil Series in Oklahoma as Suggested by USDA/NRCS
Map compiled by Elena Jigoulina

Oklahoma may be attributed to the presence of halite in Permian formations close to the surface in the far western part of the state and in the Panhandle region (Johnson, 1979). The ground water is believed to percolate down through the salt bearing Permian rocks where it dissolves the salt and eventually emerges as salt springs in alluvial deposits at lower elevations (Fig. 2.11)(Ward, 1961). As the salt is removed its margin probably shifts westward leaving patches of salt east of the main body of salt deposits (Ward, 1961). These patches of salt may account for the developing of sodic soils in western Oklahoma. The soils studied are located in areas where Dog Creek, Garber, Hennessey, Wichita, and Wellington units outcrop (Table 2.7). These formations containing salt deposits and composed chiefly of red and gray gypsiferous shale and siltstone and fine-grained sandstone containing massive beds of gypsum and anhydrite (Ward, 1961) are responsible for the sodic soil formation on the uplands (the Wing and Hinkle soils, at sites 18 and 23, respectively).

Sodic soils on terraces and floodplains in the east and central parts of Oklahoma are formed in salty alluvium deposited along the rivers (Canadian, Arkansas, Cimarron, Red) flowing through salt bearing rocks upstream (Appendix A; Ward, 1961). Salt-bearing bedrock in central and eastern Oklahoma (Snider, 1917) accounts for salt accumulation and consequent sodic soil formation in alluvial deposits via the presence of a shallow saline water table. Soils formed in alluvium may have received salts from ground water supplied by underflow from an adjacent stream (Dott, 1942) with highly saline water. The master streams of Oklahoma, the Red River, the Arkansas River, the Canadian River, the North Canadian River, the Cimarron River, and the Salt Fork of the Arkansas River, along which most of the sodic soils occur, flow from the west to the southeast and receive

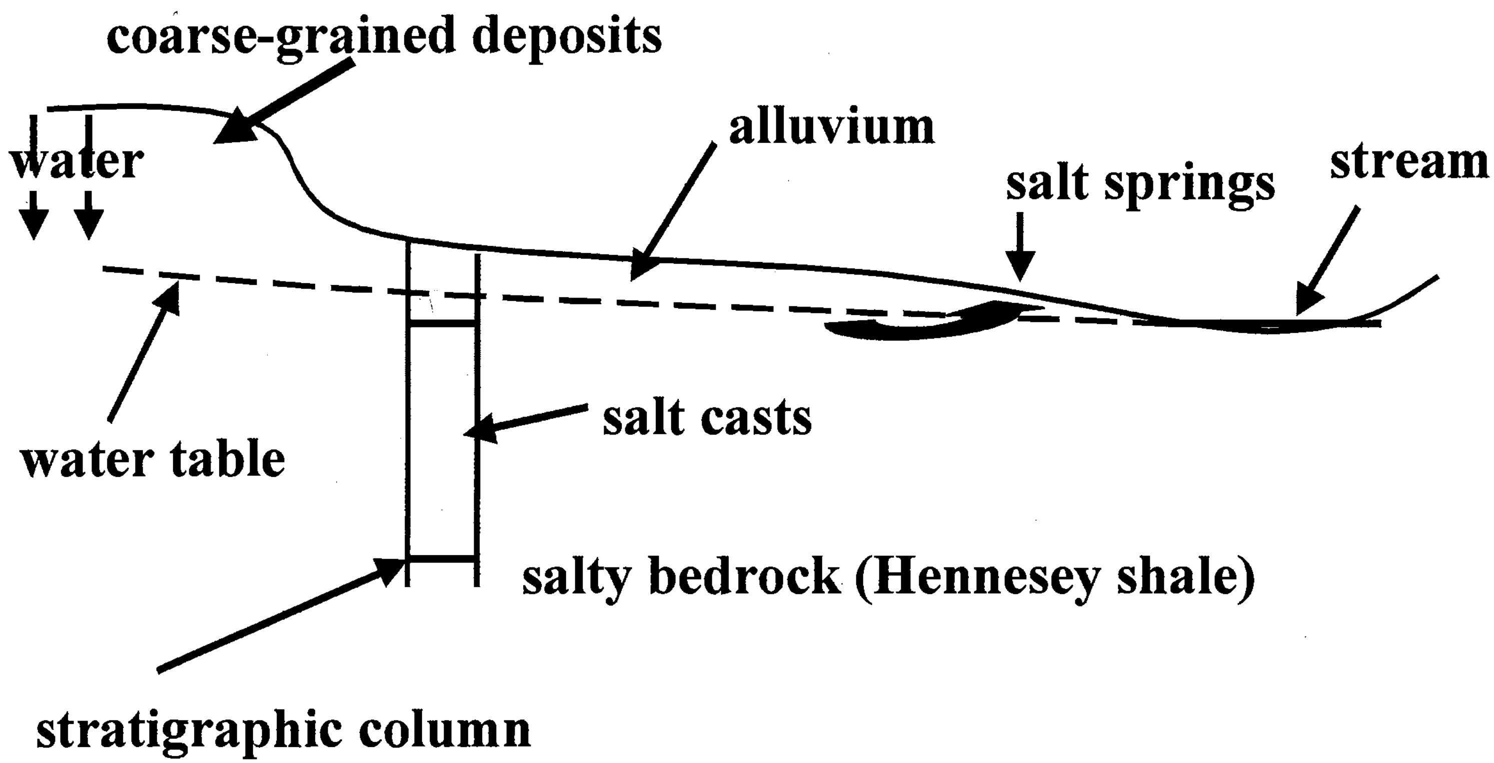

Fig. 2.11. Saline-Sodic Soil Development from Salt-Saturated Alluvium
Source: Ward (1961)
Diagram compiled by Elena Jigoulina

salt and gypsum dissolved from the Permian Redbeds upstream (Ward, 1961; Fay, 1962; Marine and Schoff, 1962; Fay, 1978; Holdoway, 1978; Green et al., 1999). Only the Red River and the Arkansas River alone receive up to 8,000 tons of sodium chloride per day from salty formations in southwestern Kansas, western Oklahoma and northwestern Texas (Ward, 1961).

Residual sodic soils in the eastern part of Oklahoma are formed in deposits of Pennsylvanian age, McAlester shale (the Wister soil), Thurman sandstone (the Dwight soil, site 8), and Red Eagle limestone (the Dwight soil, site 11). Extensive salt deposits are not documented in these formations, though it may be hypothesized that there were local salt lenses deposited during the Pennsylvanian period when the area stood near sea level (Snider, 1917).

Non-sodic, non-saline, limy deposits of sand, clay, gravel, and caliches of Tertiary age deposited from ancient rivers draining the Rocky Mountains (Gray and Galloway, 1959; Marine and Schoff, 1962; Fay, 1978; Branson, and Johnson, 1979) did not give a rise to sodic soils in the Panhandle and west central regions though climatic conditions are favorable for sodic soil formation. Deposits in the far west part of the state are mostly sandstones that produced well-drained permeable soils. Limestone underlying the far northeast part of the state resulted in the formation of nonsaline, nonsodic soils (Fig. 2.10).

Effect of Topography and Water Table Presence on Sodic Soil Properties

All soils studied were found on broad valleys with low slope of 0-5% on uplands, terraces, and floodplains (Table 2.8). The soil of the Bosville series has a slope of 4-8%. Johnson (1985) and Kellog (1934) also found sodic soils in depressions, and Whittig and Janitsky (1967) and Levy (2000) reported the presence of sodic soils on low slope gradients.

Jenny (1941) noted that topography influences soil moisture conditions via proximity of water table and modification of the amount of precipitation the soil receives. Drainage conditions and depth of water table for soils studied are presented in Table 2.8. At the time of sampling, a water table was found at four sites and was saline and sodic (Table 2.9). Ground water composition significantly affects sodic soil occurrence. In areas with low amounts of soluble salts in ground water (the Panhandle area, the North East) there are no sodic soils mapped. In eastern and east central Oklahoma, where ground water is of fair quality in general, sodic soils are found in places with pockets of highly mineralized ground water (Warren, 1952; Motts, 1963). In western Oklahoma, where extensive amounts of soluble sodium salts are found in the ground water, sodic soils are widespread. Local stratigraphy and topography exerts a strong effect on the ground water movement (Ward, 1961) and hence on sodic soil formation by determining areas of salt accumulations. Presence of a high water table for most of the year in the Lafe soil accounted for the largest range and different distribution of salinity along the profile compared to other soils in the udic group. In the subhumid subgroup of the udic ustic group the Drummond soils with a high water table (sites 10 and 12) had similar

Table 2.8

LANDSCAPE POSITION AND DRAINAGE CHARACTERISTICS OF SOILS UNDER STUDY

Series (site number)	Landscape Position	Slope %	Water table depth	Water table season*	Drainage#	Water table depth at sampling time¶
						---------cm---------
Bosville (1)[1]	high terrace	4-8	perched, 30-60 cm	W, Sp	mod. well	nf
Dwight (2)[2]	high terrace	1-3	NA	NA	mod. well	nf
Wing (3)[3]	low terrace	0-2	perched, 15-30 cm	W, Sp	mod. well	nf
Wister (4)[3]	uplands	0-1	perched, 30-60 cm	W, Sp	mod. well	nf
Pawhuska (5)[4]	high terrace	0-3	NA	NA	mod. well	200 (July)
Lafe (6)[5]	low terrace	0-2	NA	NA	somewhat poor	170 (July)
Carytown (7)[6]	low terrace	0-1	perched, <30 cm	W, Sp	poorly drained	nf
Dwight (8)[7]	uplands	0-1	NA	NA	mod. well	nf
Doolin (9)[8]	high terrace	0-3	NA	NA	mod. well	nf
Drummond (10)[9]	low terrace	0-1	1-3 m	W, Sp	somewhat poor	164 (July)
Dwight (11)[10]	uplands	0-3	NA	NA	mod. well	nf
Drummond (12)[11]	low terrace	0-1	60-180 cm	W, Sp	somewhat poor	122 (July)
Doolin (14)[12]	high terrace	0-2	NA	NA	mod. well	nf
Carytown (15)[13]	high terrace	0-1	less than 46 cm	W, Sp	poorly	nf
Seminole (16)[12]	low terrace	0-2	perched, 30-60 cm	Sp	mod. well	nf
Healdton (17)[14]	low terrace	0-1	perched, 15-46 cm	most of the year	mod. well	nf
Wing (18)[15]	uplands	0-3	NA	NA	somewhat poor	nf
Oscar (19)[15]	low terrace	0-1	Subject to flooding		mod. well	nf
Foard (20)[16]	low terrace	0-1	NA	NA	mod. well	nf
Oscar (21)[17]	low terrace	0-1	NA	NA	mod. well	nf

Table 2.8, cont'd

Series (site number)	Landscape Position	Slope %	Water table depth	Water table season*	Drainage#	Water table depth at sampling time¶
						---------cm---------
Hinkle (22)[18]	high terrace	0-1	NA	NA	mod. well	nf
Hinkle (23)[19]	uplands	0-3	NA	NA	mod. well	nf

* - W – winter, Sp – spring
\# - mod. – moderately
¶ - nf = not found within 200 cm depth at the time of sampling
[1] – slope and water table data from Swafford and Reasoner (1979)
[2] - slope and water table data from Shingleton (1971)
[3] – slope and water table data from Abernathy et al. (1983)
[4] - slope and water table data from Moebius and Sparwasser (1979)
[5] - slope and water table data from Abernathy (1970)
[6] – slope and water table data from Townsend (1988)
[7] - slope and water table data from Sparwasser et al. (1968)
[8] - slope and water table data from Boutlier et al. (1987)
[9] – slope and water table data from Fisher and Swafford, 1976
[10] - slope and water table data from Boutlier et al. (1979)
[11] – slope and water table data from William et al. (1985)
[12] – slope and water table data from Henley et al. (1987)
[13] – slope and water table data from Cole et al. (1977)
[14] - slope and water table data from Moebius and Maxwell (1979)
[15] – slope and water table data from Mobley and Ringwald (1979)
[16] - slope and water table data from Mobley and Brinlee (1967)
[17] - slope and water table data from Lamar and Rhodes (1974)
[18] - slope and water table data from Lamar (1979)
[19] - slope and water table data from Bogard et al. (1978)

TABLE 2.9

CHEMISTRY OF GROUND WATER AT SELECTED SITES UNDER STUDY

Soil Series (Site Number)	Concentrations of Ca^{+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	CO_3^{2-}	HCO_3^{-}	SAR	pH	EC
	------cmol/L------										dS/m
Lafe (6)	0.1	0.35	4.21	0.0	0.04	2.01	0.13	0.78	28.3	7.5	3.8
Drummond (10)	0.33	0.49	4.06	0.0	1.34	0.98	0.03	1.02	20.1	8.0	4.0
Drummond (12)	0.81	0.87	6.84	0.0	4.83	2.79	0.1	0.83	23.5	7.1	6.6

salinity value ranges but different distribution of salinity along the profile resulted from difference in some other properties like texture for example. Ground water obviously plays a significant role in formation and variability of sodic soils in Oklahoma and needs further study. Presence of a shallow water table was reported to be a principal factor in sodic soil development in any climate zone by a number of authors (de Sigmond, 1926; Gedroitz, 1927; Kellog, 1934; Kelley, 1934; Murphy and Daniel, 1935; MacGregor and Wyatt, 1945; Bentley and Rost, 1947; Kelley, 1951; Westin, 1953; Fedorin, 1960; Wittig and Janitzky, 1967; Arshad and Pawluk, 1966; Szabolcs, 1979; Fullerton and Pawluk, 1987; Hopkins et al., 1991; Miller and Pawluk, 1994; Seelig and Richardson, 1994) resulting in the intrazonal nature of sodic soils.

The effect of saline ground water on saline and sodic soils distribution is modified by local stratigraphy and topography. Under certain geologic and hydrologic conditions, ground water that percolates down and through salt bearing rocks where it dissolves salts emerges as salt springs in alluvium at a lower elevation (Ward, 1961).

Sodic soil properties (acidity, pH, salinity, and SAR), especially in an area with high P-E index (average P-E index of more than 90), varied with landscape position. Seelig and Richardson (1994) recorded that each landform position has at least one type of sodic soil as a result of redistribution and concentration of sodium salts via lateral and upward water movement from a shallow water table. Seelig and Richardson (1994) found sodic soils on uplands above areas where moisture is trapped in relatively shallow course-textured substrata. Seelig and Richardson (1994) and Seelig et al. (1990a, 1990b) pointed to an intimate relationship between sodic soil properties and position on a landscape. A close relationship between sodic soil properties and moisture conditions has been discussed in several papers (Gedroitz, 1927; Kellog, 1934; Kelley, 1934; Murphy and Daniel, 1935; MacGregor and Wyatt, 1945; Bentley and Rost, 1947; Kelley, 1951; Westin, 1953; Wittig and Janitzky, 1967; Arshad and Pawluk, 1966; Fullerton and Pawluk, 1987; Hopkins et al., 1991; Miller and Pawluk, 1994; Seelig et. al., 1990; Seelig and Richardson, 1994).

Effect of Climate on Sodic Soil Properties

Soil Color. Topsoils of the typic ustic and subhumid subgroups of udic ustic groups have a redder hue (5 or 7.5 YR) compared to other groups having colors in a browner hue of 10YR (Table 2.10). Subsoil of the udic humid-wet subgroup has more variety in hue values than subsoils from other udic subgroups, udic ustic, and typic ustic groups. The exception is the soils of Dwight series (sites 2, 8, 11), which had fairly uniform color throughout the profile regardless of climatic settings and explained, probably, by the prevailing effect of the parent material (Table 2.7). This fact supports data of the Oklahoma Geological Survey (1998; http://www.ou.edu/special/ogs-pttc) that in Oklahoma soils in west are red in color due to iron oxides present in bedrock and soils elsewhere have shades of brown, gray, and black. Effect of parent material on the soil color was noted also by Schwertmann (1993). Differences in the age of the soils studied could also account for color variations between the soils. Effect of time on soil color was reported by Birkeland (1999).

Redoximorphic features contribute significantly to the coloration of sodic soils and are more dependent on climatic conditions. They were prominent or/and distinct in udic

TABLE 2.10

COLOR, STRUCTURE, AND REDOXOMORPHIC FEATURES OF THE SOILS STUDIED

A-horizon (s)		B-horizon (s)		Location of	Redoxomorphic depletions#			
color hues	structure*	color hues	structures*	siltans,	location	abundance	contrast	size
				----------------cm----------------				
					Udic			
					Humid-wet			
					Site 1: Bosville soil series			
10YR	sbk	7.5YR 2.5Y 10YR	sbk, pr	28+	53-168	few	prominent	fine to coarse
					Site 2: Dwight soil series			
10YR	sbk	10YR	pr	36-110	-			
					Site 3: Wing soil series			
10YR	sbk	10YR gley 2.5Y 7.5YR/N5/0	pr, sbk	-	20 72-115 115-170+	gley layer common mtl	 distinct	 medium
					Site 4: Wister soil series			
10YR	sbk	10YR 2.5Y 2.5YR/5YR	sbk…	-	78+	mtl		
					Site 6: Lafe soil series			
2.5Y	pl	10YR 2.5Y 7.5YR/10YR	sbk, pr	-	12-95	few, common	distinct, faint	fine to coarse
					Subhumid-humid			
					Site 7: Carytown soil series			
10YR	gr	7.5YR 10YR	sbk, pr	22-49	49+	common, many	distinct, prominent	coarse
					Site 8: Dwight soil series			
10YR	sbk	10YR	pr…	19-61	61-105	many	prominent	many

TABLE 2.10, cont'd

A-horizon		B-horizon		Location of	Redoxomorphic depletions#			
color hues	structure*	color hues	structures*	siltans,	location	abundance	contrast	size
				-----------------cm-----------------				
					Subhumid			
					Site 15: Carytown soil series			
10YR	sbk	10YR 2.5Y 5Y	pr, sbk	-	100+	many, common	faint, prmt, dct	fine
					Udic ustic			
					Humid			
					Site 11: Dwight soil series			
10YR	sbk	10YR 2.5Y	cln, sbk	0-67	67-95	many	distinct	many
					Humid-subhumid			
					Site 5: Pawhuska soil series			
10YR	pl	10YR	pr…	23-55	120-210	few	faint	fine
					Site 9: Doolin soil series			
10YR	gr, pr	10YR	pr, sbk	23-56	-	-	-	-
					Site 14: Doolin soils series			
10YR	gr	7.5YR 10YR	pr, sbk	-	92-166	many	prominent	coarse
					Site 16: Seminole soil series			
10YR	gr	10YR 7.5YR	pr, sbk	-	137-193	common	prominent	medium
					Site 17: Healdton soil series			
10YR	sbk	10YR	cln, sbk	13-56	91-123	common	faint	fine
					Site 23: Hinkle soil series			
7.5YR	pl	2.5YR	pr	18-74	18-48 48-74	ped coat few strata		
					Subhumid			
					Site 10: Drummond soil series			
10YR	sbk	10YR	sbk	26-54	26-54 117-164	few common	faint distinct	fine medium

TABLE 2.10, cont'd

A-horizon		B-horizon		Location of	Redoxomorphic depletions#			
color hues	structure*	color hues	structures*	siltans,	location	abundance	contrast	size
				------------------cm------------------				
					Site 12: Drummond soil series			
7.5YR	sbk	7.5YR 5YR	sbk, pr	19-40	-	-	-	-
					Site 18: Wing soil series			
7.5YR	gr, m	7.5YR	pr, sbk	27-77	77-97 97-155	common gley	prominent	medium
					Site 19: Oscar soil series			
5YR	pl	7.5YR	pr, sbk	15-110	-	-	-	-
					Typic ustic			
					Site 20: Foard soil series			
7.5YR	pl	7.5YR	cln, sbk	0-122	122-209	few (in channels)		fine
					Site 21: Oscar soil series			
10YR	pl	10YR	cln, sbk	9-57	-	-	-	-
					Site 22: Hinkle soil series			
7.5YR	sbk	7.5YR	pr…	0-41	-	-	-	-

* - sbk – subangular blocky, cln – columnar, pl – platy, gr – granular, m – massive,
# -abundance: mtl – mottled horizon; contrast: prmt – prominent, dst - distinct

group soils and were mostly faint or absent in soils of the subhumid-humid subgroup of the udic ustic group and were mostly absent in soils of the subhumid subgroup of the udic ustic group and typic ustic group, resulting in more uniform color of latter.

Redoximorphic Features. Redoximorphic depletions are found in most soils of all groups (Table 2.10). They are more common at shallower depths in soils of the udic group than in soils of the ustic group. The amount of soils with redox depletions decreases with a decrease in P-E index. Presence of redoximorphic depletions in sodic soils of all groups results from the impeded drainage and climatic conditions of the area.

Soils in areas with the lowest P-E indexes (subhumid subgroup of the udic ustic group and the typic ustic group) may have a shallow water table for shorter periods than soils of the udic groups, which explains the absence of redox depletions in some of them (Table 2.10). The fact that the shallow water table was documented for only 9 sodic soils containing mapping units of Oklahoma (Table 2.8) does not allow inference about its effect on sodic soil properties.

Soil Texture. Most sodic soils studied (except the Dwight soil in Pittsburg and Pawhuska soil in McClain) have a maximum clay content in the B horizon, and all soils showed a sharp increase in clay content between the lower A or E horizon and upper B (more than 7%) (Table 2.11), which is common for sodic soils. The highest increase in clay content in a subsurface is recorded for a soil located in the region where precipitation is equal to evaporation (the Wister soil, site 4). There is a slight increase in clay content in soils of the udic group compared to soils of the udic ustic and typic ustic groups. Minimum percent of clay in soils of the udic group is recorded for the Dwight soils (sites 2 and 8). To record a change in textural class a modified Bilzi-Ciolkosz

TABLE 2.11.

TEXTURAL CHARACTERISTICS FOR SOILS STUDIED

Soil series (Site number)	Maximum clay content			Change in textural class* #	Difference in clay content between A(E)-B, %
	%	horizon (s)	depth, cm		
				Udic	
				Humid-wet	
Bosville (1)	44	Bt1, Bt2	28-76	1, 1, 3, 3, 4, 4, 4, 4,	35
Dwight (2)	47	BC	140+	1, 2, 2, 2, 3, 3	11
Wing (3)	48	Bty2	41-72	1, 3, 4, 5, 5	29
Wister (4)	73	Bt1	25-55	1, 1, 3, 3	50
Lafe (6)	43	Bty2, Btky3	30-95	1, 3, 4, 5, 6, 7	21
				Subhumid-humid	
Carytown (7)	44	Btn1	22-49	1, 3, 3, 3, 4, 5	32
Dwight (8)	34	Btk3	105-152	1, 1, 2, 3, 3	16
				Subhumid	
Carytown (15)	48	Btny3	76-100	1, 2, 3, 5, 7, 8, 9	21
				Udic ustic	
				Humid	
Dwight (11)	56	Btn2	38-67	1, 2, 2, 2, 3, 4, 5	10
				Humid-subhumid	
Pawhuska (5)	46	BC	150+	1, 2, 2, 2, 2, 3	20
Doolin (9)	42	Btn1	23-56	1, 3, 4, 4, 5, 5	29
Doolin (14)	43	Btn1	24-49	1, 3, 4, 4, 4, 5, 5	32
Seminole (16)	42	Btn1	34-57	1, 1, 3, 3, 4, 7	22¶
Healdton (17)	50	Btn2	39-56	1, 3, 3, 4, 4, 4, 4, 4	37
Hinkle (23)	35	Btnss1	18-48	1, 2, 2, 3, 3	19
				Subhumid	
Drummond (10)	56	Btss2	54-91	1, 2, 2, 2, 4	15
Drummond (12)	40	Bty1,b	56-79	1, 2, 3, 4, 5, 5	10&
Wing (18)	34	Btn1	27-53	1, 2, 3, 4, 4, 4, 4, 7	22
Oscar (19)	24	Btnky, Bt4	15-38, 110-173	1, 2, 2, 2, 2,2	

TABLE 2.11, cont'd

Soil series (Site number)	Maximum clay content			Change in textural class* #	Difference in clay content between A(E)-B, %
	%	horizon (s)	depth, cm		
				Typic ustic	
Foard (20)	45	Btnky3-BCk	60-169	1, 3, 3, 3, 3, 3, 3	23
Oscar (21)	41	Btnky2	25-37	1, 2, 3, 4, 5, 6, 6, 7	18
Hinkle (22)	53	Btnky2	41-58	1, 3, 3, 4, 4, 5, 6	22

* - explanation in text
¶ - difference in clay content between BA and B
& - difference in clay content between buried A and buried B

scheme was used (Bilzi and Ciolkosz, 1977; Birkeland, 1999). A change in textural class is worth one point, surface is assigned number 1. Also textural class between the A (E) and upper B horizon changed more distinctly in soils of areas with a mean P-E of more than 63 (the udic group, subhumid, and humid-subhumid subgroups of the udic ustic groups) compared to soils with a mean P-E equal to or less than 63 (subhumid subgroup of the udic ustic group, and Oscar soil of the typic ustic group). Jenny (1935) found that clay content of a soil correlate linearly with moisture and exponentially with temperature. Westin (1976) and Birkeland (1999) also reported climate effect on clay accumulation. The modifying effect of parent material on clay content-climate relationships was noted by Ruhe (1984) and of dust influxes and soil age by Birkeland (1999).

Parent material also controls absolute amounts of clay, silt, and sand particles in soils studied (Table 2.12). The effect of parent material on soil texture is documented (Westin, 1976; Brady and Weil, 1996).

Soil Structure. Soils of the udic group have blocky structure over prisms with the exception of soils in the Dwight soils (sites 2 and 8) and Wing soil (site 3). With the exception of Drummond soils, soils of the subhumid subgroup of the udic group and soils of the udic ustic and typic ustic groups displayed prismatic structure over the blocky structure (Table 2.10). In areas with udic soil moisture regime, the transformation of sodic soils into leached sodic (Solods) may have started and resulted in disintegration of the prisms into blocks. Disintegration of prismatic structure in Solods (leached sodic soils) was recorded in Canada (Agriculture Canada Expert Committee, 1987). In areas with a long history of cultivation, like some areas in Oklahoma, plowing may result in structure change of the soil surface and upper B-horizon. Variations in structure between

TABLE 2.12

CLAY, SILT, AND SAND CONTENT OF SODIC SOILS STUDIED

Soil series (Site number)	A-horizons* clay	A-horizons* sand	A-horizons* silt	B-horizons* upper B	B-horizons* clay range	B-horizons* lower B	B-horizons* sand range	B-horizons* silt range	C-horizons* (or BC) clay	C-horizons* (or BC) sand range	C-horizons* (or BC) silt range
	%			%					%		
					Udic Humid-wet						
Bosville (1)	6-8(E)	35	58	44	30-44	30	24-41	30-51	33 (BC)	22	45
Dwight (2)	22	16	63	33	33-41	41	4-9	55-59	47 (BC)	2	51
Wing (3)	13	18	69	42	42-48	48#	7-13	41-48	44 (2BC)	14	42
Wister (4)	16-23(E)	18	66	73	51-73	51	3-6	24-44	26 (Cr)	5	69
Lafe (6)	18	34	47	39	39-43	40	17-20	34-44	40 (BC)	27	34-66
					Subhumid-humid						
Carytown (7)	12 (E)	26	62	44	37-44	37	12-22	39-45	-	-	-
Dwight (8)	11	26	62	27	27-34	29	19-22	43-54	29 (BC)	24	46
					Subhumid						
Carytown (15)	16	23	60	37	27-48	27	9-47	5-65	27(2Cr)	7	66
					Udic ustic subhumid						
Dwight (11)	34	5	62	44	44-56	52	3-11	43-45	34(C)	19-23	43-66
					Humid-subhumid						
Pawhuska (5)	18	24	57	38	37-38	38	11-15	46-51	46(BC)	22	32
Doolin (9)	13	16	71	42	38-42	41	9-15	46-51	41(2BC)	12	46
Drummond (10)	32	26	42	47	47-56	55#	10-39	28-36	-	-	- -
Drummond (12)&	37-10(Ap2)	2-11	61-78	40	29-40	33	3-7	57-65	-	-	- -
Doolin (14)	11	31	58	43	27-43	27	19-55	16-39	27(2R)	57	15
Seminole (16)	18-20(BA)	44	38	42	33-42	33	29-47	20-42	15-16(2Cr)	76	7-10
Healdton (17)	11	38	51	48	42-50	44$	11-14	39-44-	-	-	-
Wing (18)	9-12(Ap2)	50-62	26-37	34	28-34	30	36-47	23-30	10-26(BC, C)	56-79	11-17
Oscar (19)	17	28	55	24	22-24	24	32-47	31-43	23(BC)	37	39
Hinkle (23)	16	25	59	35	28-35	28	13	51-59	22-19(C)	12-23	57-66

TABLE 2.12, cont'd

Soil series (Site number)	A-horizons* clay	A-horizons* sand	A-horizons* silt	B-horizons* upper B	B-horizons* clay range	B-horizons* lower B	B-horizons* sand range	B-horizons* silt range	C-horizons* (or BC) clay	C-horizons* (or BC) sand range	C-horizons* (or BC) silt
	---%---			---%---					---%---		
					Typic ustic						
Foard (20)	20	11	70	43	41-45	45	5-7	49-53	45(BC)ξ	5	50
Oscar (21)	19	19	62	37	26-41	26	4-23	49-59	21-26(BC, C)	17-37	43-57
Hinkle (22)	19	22	59	41	24-53	24	5-20	42-56	22(BC)	22	56

* - first number in a range data for upper layer
# - 2B is not included
$- buried horizons are not included
& - data for buried A: clay – 30, sand – 6, silt –64; B horizons are buried
ξ - 2C not included

soils may be the result of different sodium content. Usually sodic soils have prismatic or columnar structure in the subsurface (Agriculture Canada Expert Committee, 1987; Kaurichev, 1989; Soil Survey Staff, 1999). In this study, most of the soils of the udic ustic and typic ustic groups showed a large sodium content (SAR of ≥13) in horizons with prisms or columns (Table 2.13). In contrast, most soils of the udic group had SAR less than 13 in horizons with prismatic structure. Horizons with columnar structure had SAR more than 13 (Table 2.13). Climate, soil salinity, acidity, and other factors may modify high sodium content effect on a subsoil structure. Soil of the Wister series (site 4) does not have prisms, which may be due to high acidity. In sodic soils, structure may be related to dispersion phenomenon, which is discussed in corresponding section. Soil structure is the only field criterion used for sodic soil identification (Soil Survey Staff, 1999). This study showed that prismatic structure alone faces cannot be sufficient to infer a large sodium content (Table 2.13). Other studies have shown that the presence of columns or prisms in a soil subsurface is not always evidence of a large sodium content on the exchange (Kelley, 1934; Kelley, 1951; White, 1964a; White, 1964b; Isbell, 1996).

Siltans. The presence of siltans was recorded for most soils of the ustic and udic ustic groups and only in some soils of the udic group (Table 2.10). The amount of soils with siltans gradually increases with decreasing P-E index. Siltans, bleached silt and sand grains along soil structural units, are attributed to dispersion, which makes clay particles very mobile and is enhanced by large sodium content. Factors that affect dispersion affect siltans formation. Dispersion phenomenon and factors it depends on are discussed in the Physical Properties section.

TABLE 2.13

PRISMATIC STRUCTURE AND SAR IN SOILS STUDIED

Soil Series (Site Number)	Horizon with prismatic or columnar structure*	Depth	SAR
	Udic		
	Humid-wet		
Bosville (1)	Bt2	53-76	5.1
	Bty4	130-168	7.7
	BC	168-200+	11.8
Dwight (2)	Bn1	17-36	4.9
	Bn2	36-64	8.7
Wing (3)	Bt1	20-41	23.4
Lafe (6)	Bty2	30-55	30
	Btky3	55-95	17.3
	Humid-subhumid		
Carytown (7)	Bt2	49-89	9.9
	Bty3	89-119	10
	Bty4	119-150	9.9
	Bty5	150-193+	8.2
Dwight (8)	Bn1	19-61	10.7
	Btk2	61-105	22.8
	Btk3	105-152	23.4
	BCk	152-193+	18.6
	Subhumid		
Carytown (15)	Btn1	19-37	19.2
	Udic ustic		
	Humid		
Dwight (11)	Btn1 (clmn)	13-38	20
	Btn2 (clmn)	38-67	28.4
	Humid-subhumid		
Pawhuska (5)	Bn1	23-55	12.2
	Bty2	55-81	11.6
	Btk3	81-120	18.0
	Bt4	120-150	20.8
	BC	150-210	19.8
Doolin (9)	Ap2	9-23	2.8
	Btn1	23-56	17.4
	Btk4	107-160	2.6
Doolin (14)	Btn1	24-49	16.3
	Btkn3	69-92	14.8
	Btnyq4	92-136	21.3

TABLE 2.13, cont'd

Soil Series (Site Number)	Horizon with prismatic or columnar structure*	Depth	SAR
	Humid-subhumid, cont'd		
Seminole (16)	BAn	21-34	4
	Btn1	43-57	13.7
Healdton (17)	Btn1(clmn)	13-39	19.5
	Btk4	91-123	26.5
	Akss, b	123-151	27
	Btkss1, b	151-186	26.9
	Btkss2, b	186-202	18.6
Hinkle (23)	Btnss 1	18-48	32.2
	Btk2	48-74	37.2
	Subhumid		
Drummond (10)	2Bt4	117-164	33.5
Drummond (12)	A1, b	40-56	26.4
	Bty1, b	56-79	23.2
	Btk2, b	79-117	22.2
	Btk3, b	117-148	31.5
Wing (18)	Btn1	27-53	39.8
Oscar (19)	Btnky1	15-38	62.6
	Btnky2	38-78	74.4
	Btn3	78-110	50.9
	Typic ustic		
Foard (20)	Btn1 (clmn)	10-32	13.7
	Btnky3	60-90	14.9
	Btkny4	90-122	17.3
Oscar (21)	Btkyn1 (clmn)	9-25	51.7
	Btkn5	87-118	85.4
Hinkle (22)	Btkn1	18-41	25
	Btkyn2	41-58	24.2
	Btkn3	58-77	29.3
	Btkn4	77-107	31.2
	Btkn5	107-157	30.8
	BCk	157-200	29.9

* - clmn=columnar structure

Carbonates, Gypsum, and Soluble Salts. In this study carbonates are absent, or the top of the carbonate bearing horizon is found at greatest depth in soils of the udic group, especially in those with the highest P-E range (humid-wet climate) compared to other groups (Table 2.14). Soils of the typic ustic group have the shallowest location of the top of the carbonate bearing horizon. Greater depth to the horizon with calcium carbonate in more humid environments has been recorded by Birkeland (1999). Still another factor to be considered is the calcium content of parent materials because Jenny (1941b) has shown that $CaCO_3$ horizons can persist at higher values of precipitation in soils with calcium-rich parent materials relative to parent materials low in calcium. The example in this study is the Dwight soil (site 11), which though located in an area with relatively high P-E index has a carbonate-bearing horizon much closer to the surface compared to soils with a similar P-E index. Carbonate in soils of the humid-wet subgroup of the udic group may appear in soil due to capillary rise from perched ground water.

Gypsum accumulations are located closer to the surface in soils of the typic ustic group compared to soils of the udic and udic ustic groups. Gypsum is found in all soils of the typic ustic group and in most soils of the udic ustic one. There is a great variation in gypsum presence and occurrence inside the climatic groups, reflecting, probably, different drainage conditions (the Lafe and Carytown soils) and ground water (the Drummond soil at site 10, and the Lafe soil) and parent material composition (Table 2.7). Allen and Hajek (1989) reported that much of the gypsum in substrata of the soils is inherited from gypsum containing parent materials and that in humid regions gypsum occasionally occurs in poorly drained or very slowly permeable soils. Gypsum in soils studied may accumulate at depths reached by mean annual soil water (Birkeland, 1999)

TABLE 2.14

DEPTH TO SOLUBLE SALTS, CARBONATES, AND GYPSUM IN SOILS STUDIED

Soil Series (Site number)	Depth to horizon with#										
	carb	gypsum	pH	max sal	sal≥2	max Cl	max SO4	max Na	max SAR	Bt	SAR≥13
	---------------	---------------	---------------	---------------	---------------	cm	---------------	---------------	---------------	---------------	---------------
Udic											
Humid-wet											
Bosville (site 1)	-	130	200+	168	168	168	168	168	168	28	nf
Dwight (site 2)	-	-	36	64	nf	140	64	110	140-170	17(Bn)	nf
Wing (3)	115+	72-115	170+	41	41	0-20	41	41	72-115	20	20
Wister (4)	-	-	105+	105	nf	105	105	105	105	25	105
Lafe (6)	95-170	55-140	140	12	12	0-12	0-12	0-12	30-55	12	surface
Udic-humid											
Carytown (7)	-	49+	89	119	22	6-22	89-119	89-119	22-150	22	nf
Dwight (8)	61+	-	193	61	61	61-105	105-152	61-105	61-152	19	61
Subhumid											
Carytown (15)	76-100	76-100	172+	76	37	138-172	76-100	76-100	138-172	19	19
Udic ustic											
Humid											
Dwight (11)	13	-	109	67	13	38-67	38-67	38-67	95-109	13	13
Subhumid-humid											
Pawhuska (5)	81-150	55-81	55	55	55	150	55-81	55-81	120+	23 (Bn)	81
Doolin (9)	81+	56-107	210	81	56	107-160	81-107	56-81	23-56	23	23
Doolin (14)	69-92	92-136	184	69	49	69-92	69-92	69-92	92-136	24	24
Seminole (16)	97-137	97-137	193+	97	97	97-137	97-137	97-137	193+	34	34
Healdton (17)	56+	-	186	56	13	56-91	56-91	56-91	123-186	13	13
Hinkle (23)	48+	-	104	48	18	0-18	18-48	48-74	74-104	18	18
Subhumid											
Drummond (10)	26-54	-	91	26	surface	0-26	0-26	0-26	26-54	26	surface
Drummond (12)	79	56	148	56	19	40-56	56-79	56-79	117-148	56	19
Wing (18)	77-137	-	137	77	surface	77-97	77-97	77-97	77-97	27	27
Oscar (19)	15-78	15-78	110	15	surface	15-38	15-38	15-38	38-78	15	surface

TABLE 2.14, cont'd

Soil Series (Site number)	Depth to#										
	carb	gypsum	pH	max sal	sal≥2	max Cl	max SO4	max Na	max SAR	Bt	SAR≥13
	--cm--										
				Typic ustic							
Foard (20)	32+	32-122	169	122	surface	122-169	60-90	122-169	122-169	10	10
Oscar (21)	9+	9-37	57	25	surface	25-37	25-37	25-37	87-118	9	surface
Hinkle (22)	18+	41-58	157	58	18	58-77	41-58	41-58	77-107	18	18

- carb = carbonates, sal = salinity, max = maximum, nf = not found at a depth of sampling

or precipitate during evaporation of upward moving waters from a shallow water table or during evaporation of shallow ponds (Watson, 1985).

The presence and location of salts more soluble than gypsum is dependent on climatic and drainage conditions (Tables 2.14, 2.15). Soil with EC ≥ 2 dS/m is considered to be saline (Soil Survey Staff, 1993, p.193). Depth to a horizon with EC$\geq$2 decreased and salinity increased with a decreasing P-E index. Impeded drainage and ground water composition may account for high salinity values in soils of the humid-wet subgroup of the udic group. Salinity increases with depth or has uniform values in soils of the udic group and in subhumid subgroup of the udic ustic group with the exception of Lafe soil series (site 6), which has a shallow water table for most of the year. In soils of the subhumid-humid subgroup of the udic ustic group maximum soil salinity is mostly in the middle depth of the profile (Table 2.15). In the soils with a still lower P-E index of subhumid subgroups of the udic ustic group and in soils of the typic ustic groups, the prevailing trend is decreasing soil salinity with depth with two exceptions - the Drummond soil (site 12) and the Foard soil (site 20). The Drummond soil (site 12) is located in a temperature regime bordering with mesic that may result in overall downward water movement through the profile. The Foard soil also has relatively low values for salinity in the solum compared to other soils with similar P-E indexes. Nettleton et al. (1982) found that pedogenic accumulations of salts occur at depth to which soil water penetrates during the wetter years and hence is dependent on climate. Birkeland (1999) explained salts' sensitivity to climatic changes by their high solubility.

The major anions found in soils studied are sulfate and chloride (Table 2.16). Halite deposits in western Oklahoma and coal sediments in eastern Oklahoma accounted for

TABLE 2.15

SELECTED CHEMICAL PROPERTIES OF SOILS STUDIED*

Solum						Parent material			Second parent material		
pH		EC		SAR		pH	EC	SAR	pH	EC	SAR
range	change w/depth*	range	change w/depth*	range	change w/depth*						
		-dS/m-					-dS/m-			-dS/m-	
					Udic						
					Humid-wet						
					Site 1: Bosville soil series						
6.7-7.1	no	0.1-0.6	increase	0-8	increase	7.0	2.4	12	-	-	-
					Site 2: Dwight soil series						
6.9-7.6	no	0.5-0.8	uniform	2-12	increase	7.3	0.8	12	-	-	-
					Site 3: Wing soil series						
6.1-6.8	no	0.5-4.0	middle	5-23	increase	-	-	-	7.2-8.3	1.9-3.7	26-31
					Site 4: Wister soil series						
6.1-6.9	varies	0.1-0.7	increase	2-12	increase	7.0	1.7	15	-	-	-
					Site6: Lafe soil series						
7.3-7.9	increase	5.2-11.4	decrease	17-30	varies		8.5	3.2	35 7.7-8.0	1.4-1.6	18-25
					Humid						
					Site 7: Carytown soil series						
6.0-6.7	varies	1.5-8.6	increase	4-10	increase	-	-	-	-	-	-
					Site 8: Dwight soil series						
6.7-8.6	increase	1.2-2.0	middle	2-23	increase	8.9	0.8	19	-	-	-
					Subhumid-humid						
					Site 15: Carytown soil series						
6.7-8.1	increase	0.8-7.2	middle	6-42	increase	-	-	-	8.1	1.8	36
					Udic ustic						
					Humid						
					Site 11: Dwight soil series						
8.0-8.4	increase	1.5-3.9	increase	12-33	increase	9.1	2.1	36	8.7-8.8	0.95-1.4	5-19
					Subhumid-humid						
					Site 5: Pawhuska soil series						
7.3-8.4	top B#	0.6-5.2	middle	2-21	increase	7.4	2.9	20	-	-	-
					Site 9: Doolin soil series						
7.1-7.6	middle B	0.5-7.9	middle	3-18	increase-	-	-	7.9	2.8	14	

TABLE 2.15, cont'd

Solum						Parent material			Second parent material		
pH		EC		SAR		pH	EC	SAR	pH	EC	SAR
range	change w/depth	range	change w/depth#	range	change* w/depth						
		-dS/m-					-dS/m-			-dS/m-	
					Site 14: Doolin soil series						
7.2-7.9	increase	0.7-7.2	middle	5-21	increase	-	-	-	8.4	1.3	19
					Site 16: Seminole soil series						
6.9-7.4	varies	0.3-6.8	middle	1-15	increase	-	-	-	7.3-7.6	2.5-4.3	19-22
					Site 17: Healdton soil series&						
6.8-7.7	increase	1.0-9.0	middle	3-27	increase	-	-	-	-	-	-
					Site 23: Hinkle soil series						
8.0-8.6	increase	8.0-9.6	decrease	22-37	increase	8.2-8.8	4.7-6.8	25-40	-	-	-
					Subhumid						
					Site 10: Drummond soil series						
5.8-9.0	increase	2.9-10.2	decrease	34-85	decrease	-	-	-	8.8	1.8	34
					Site 12: Drummond soil series						
7.6-8.1	varies	1.2-7.2	increase	5-32	increase	-	-	-	-	-	-
					Site 18: Wing soil series						
7.2-8.7	increase	7.0-9.8	middle¶	1-67	middle¶	8.1-8.8	2.5-4.5	30-37	-	-	-
					Site 19: Oscar soil series						
7.9-8.8	increase	0.9-9.8	decrease	16-74	middle¶	8.6	0.6	7	-	-	-
					Typic ustic						
					Site 20: Foard soil series						
7.7-8.2	increase	2.7-5.8	increase	4-17	increase	-	-	-	8.0-8.4	6.0-11.0	22-30
					Site 21: Oscar soil series						
7.8-9.0	increase	5.8-18.5	decrease	30-85	increase	8.6-8.7	2.1-2.5	15-56	-	-	-
					Site 22: Hinkle soil series						
7.3-8.9	varies	1.2-8.6	middle	11-31	increase	7.8	6.8	30	-	-	-

* - overall change with depth,
# - maximum pH is recorded for the upper B-horizon
& - buried soil is not included
¶ - maximum value is in the middle of the profile

TABLE 2.16

SOLUBLE ANIONS OF SOILS STUDIED

Solum						Parent material						Second parent material					
Ca	Mg	Na	Cl	SO4	HCO3	Ca	Mg	Na	Cl	SO4	HCO3	Ca	Mg	Na	Cl	SO4	HCO3
						$cmol_c/L$											
						Udic											
						Humid-wet											
						Site 1: Bosville soil series											
0.0-0.2	0.0-0.1	0.0-0.5	0.0-0.4	0.0-0.1	0.0-0.2	0.2	0.3	2.0	1.5	0.8	0.0	-	-	-	-	-	-
						Site 2: Dwight soil series											
0.0-0.1	0.0-0.1	0.3-0.8	0.1-0.4	0.1-0.4	0.1-0.3	0.0	0.0	0.7	0.3	0.1	0.3	-	-	-	-	-	-
						Site 3: Wing soil series											
0.1-0.9	0.0-1.3	0.4-1.1	0.0-0.1	0.2-5.3	0.0-0.2	-	-	-	-	-	-	0.0-0.1	0.1-0.2	1.9-3.6	0.0-0.1	1.6-4.1	0.1-0.5
						Site 4: Wister soil series											
0.0-0.1	0.0-0.1	0.1-0.8	0.0-0.1	0.0-0.7	0.0-0.2	0.1	0.1	1.7	0.1	1.9	0.0	-	-	-	-	-	-
						Site6: Lafe soil series											
0.4-2.4	2.1-8.6	6.1-19.1	0.1-0.2	7.7-15.6	0.2-0.3	0.0	0.1	3.3	0.0	3.9	0.6	0.0-0.1	0.1	1.5-1.6	0.1 1.1	1.0-	0.5
						Humid											
						Site 7: Carytown soil series											
0.2-2.5	0.3-13.2	0.7-8.9	0.1-0.4	0.9-29.8	0.0-0.1	-	-	-	-	-	-	-	-	-	-	-	-
						Site 8: Dwight soil series											
0.0-0.3	0.0-0.2	0.2-2.0	0.1-0.4	0.2-1.2	0.3-0.9	0.0	0.0	0.8	0.1	0.1	0.5	-	-	-	-	-	-
						Subhumid-humid											
						Site 15: Carytown soil series											
0.1-2.0	0.0-0.9	0.7-7.4	0.2-0.5	0.2-10.7	0.1-0.4	-	-	-	-	-	-	0.0	0.0	1.9	0.4	1.3	0.3
						Udic ustic											
						Subhumid											
						Site 11: Dwight soil series											
0.1-0.3	0.1-0.3	1.5-4.6	0.4-1.4	0.2-3.3	0.3-0.9	0.0	0.0	2.2	0.7	0.8	0.7	0.0-0.1	0.0	1.0-1.5	0.2-0.4	0.1	0.5-0.7
						Subhumid-humid											
						Site 5: Pawhuska soil series											
0.1-2.2	0.1-1.6	0.3-5.1	0.1-1.4	0.4-8.9	0.1-0.5	0.3	0.2	3.2	1.9	1.8	0.1	-	-	-	-	-	-
						Site 9: Doolin soil series											
0.1-2.3	0.1-3.8	0.4-7.6	0.1-2.1	0.1-10.6	0.1-0.4	-	-	-	-	-	-	0.3	0.3	2.5	1.2	1.7	0.2

Table 2.16, cont'd

Site	Solum						Parent material						Second parent material					
	Ca	Mg	Na	Cl	SO4	HCO3	Ca	Mg	Na	Cl	SO4	HCO3	Ca	Mg	Na	Cl	SO4	HCO3
	---cmol$_c$/L---																	
Site 14: Doolin soil series	0.1-2.5	0.1-2.1	0.5-7.1	0.3-1.7	0.1-9.2	0.2-0.6	-	-	-	-	-	-	0.0	0.0	1.1	0.5	0.4	0.4
Site 16: Seminole soil series	0.0-2.1	0.0-1.8	0.1-6.1	0.1-1.4	0.1-9.1	0.1-0.3	-	-	-	-	-	-	0.1-0.5	0.1-0.4	2.3-3.9	1.4	1.0-1.4	0.1-0.2
Site 17: Healdton soil series&	0.2-2.9	0.1-1.0	0.4-9.3	0.3-5.8	0.1-7.9	0.2-0.5	- -	-	-	-		-	- -	-	-	-	-	
Site 23: Hinkle soil series	0.5-1.2	1.3-1.9	7.7-13.2	3.7-4.4	4.5-8.7	0.3-0.4	0.3	0.4-0.6	4.8-8.1	2.5-4.0	0.8-1.4	0.2-0.3	-	-	-	-	-	-
Site 10: Drummond soil series	0.1-1.3	0.1-1.0	3.0-19.6	0.9-6.4	1.4-16.5	0.6-0.7	--	-	-	-		-	0.0	0.0	2.0	0.5	0.9	0.5
Site 12: Drummond soil series	0.2-2.2	0.2-2.1	0.8-10.7	0.5-3.4	0.4-13.1	0.2-0.5	--	-	-	-		- -	-		--	-	-	
Site 18: Wing soil series	0.0-0.6	0.1-0.6	0.3-12.3	0.3-8.2	0.1-5.3	0.4-0.6	0.1	0.1	2.4-3.8	1.5-3.0	0.6-1.2	0.2-0.3	-	-	-	-	-	-
Site 19: Oscar soil series	0.0-0.5	0.0-0.5	0.8-11.5	0.1-7.6	0.1-4.5	0.5-1.2	0.0	0.0	0.5	0.2	0.1	0.5	-	-	-	-	-	-
Typic ustic																		
Site 20: Foard soil series	0.3-1.2	0.2-1.2	1.1-5.4	1.8-4.2	0.3-4.3	0.2-1.0	-	-	-	-	-	-	0.8-1.4	0.6 1.2	5.6-10.8	4.9-9.4	0.6-3.7	0.1-0.6
Site 21: Oscar soil series	0.0-2.9	0.1-2.0	6.1-23.25.2-18.8		0.5-12.1	0.3-1.2	0.0-0.1	0.0-0.2	2.0-2.5	0.8-1.6	0.3-0.6	0.6-0.8	-	-	-	-	-	-
Site 22: Hinkle soil series	0.1-2.2	0.1-2.3	1.2-11.5	0.6-8.4	0.1-10.8	0.2-0.5	0.3	0.7	6.7	6.7	1.0	0.2	-	-	-	-	-	-

& - buried soil is not included

differences in soil solution chloride and sulfate composition. Sulfate from pyrite weathering is common in coal beds (Allen and Hajek, 1989). Sodic soils found in eastern Oklahoma are formed in alluvium over the Thurman sandstone, McAlester shale, and Boggy Formation (Table 2.7), which are known as coal producing areas (Moose and Suarle, 1929). Lower concentration of dissolved solids as well as a predominance of sulfate in soils of the udic group may also be attributed to the larger amount of moisture available for leaching compared to soils of the udic ustic and especially those of the typic ustic group. More mobile chloride moves with the soil water solution down and out of the profile compared to sulfate. Sodium is a dominant cation in soil solution of all soils studied (Table 2.16). The amount of sodium in solution increases in soils gradually with the increase of evaporation and decrease of precipitation. Local variations in soils of the humid-wet group of the udic group may be explained by extensive presence of a shallow water table containing sodium (Table 2.8, 2.9) in some soils (the Lafe and Wing).

Sodium Adsorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP). In soils of the udic group the depth to horizons with SAR of equal or more than 13 is more than half a meter reflecting highly leached environment compared to the udic ustic and typic ustic soil groups (Table 2.14). This trend was modified by the presence and composition of a shallow water table and parent material composition (Sites 3, 6, 7, 15). Maximum values of SAR were deeper in the profile in all soil groups, reflecting greater mobility of sodium ion compared to calcium and magnesium mobility. Also maximum values were less in soils of the udic group (Table 2.15). In soils of humid-wet and humid subgroups of the udic group (sites 3, 15 and 16) horizons with EC of more than 2 were deeper in the profile than horizons with the SAR of more than 13, while soils of the ustic group have high salinity and high SAR at the same depth. These observations support the theory that sodic soils in Oklahoma were initially formed as saline-sodic and under improved drainage and a high P-E index they became sodic and leached sodic.

Exchangeable sodium percentage (ESP) tends to be less and exchangeable acidity tends to be higher in the udic group soils than in soils of the ustic group (Table 2.17). Replacing of sodium with hydrogen on the exchange complex occurs in highly leached environments and leads to the formation of Solods (leached sodic) soils (de Sigmond, 1926; Gedroitz, 1927; Johnson et al., 1985; Kaurichev, 1989).

Soil pH. Surface pH of soils of the udic ustic and typic ustic groups tends to be more alkaline (Table 2.15). Surface pH was more uniform than subsurface soil reaction and obviously resulted from different management practices, such as liming of acid soils or acidification of alkaline ones. Subsurface pH is a better diagnostic feature for it is not affected by human activities. More soils with acid reaction in subsurface are in humid-wet subgroup of the udic group, while soils with alkaline reaction were mostly among soils of the udic ustic and typic ustic groups. Presence of low pH soils in high precipitation areas and alkaline ones in the drier regions is a well-known fact (Brady and Weil, 1996). The Dwight soil, located in a region with a relatively high P-E index, has a higher pH than other soils with similar P-E indexes and is explained either by calcareous parent material (strong effervescence along the profile) or by the presence of soda, which results in high pH (Brady and Weil, 1996). Parent material reaction tended to be more alkaline in soils of the udic ustic and typic ustic groups compared to soils of the udic group (Table 2.15).

TABLE 2.17

CEC, ESP, AND EXCHANGEABLE ACIDITY OF SELECTED PROFILES AND HORIZONS OF THE SOILS STUDIED

Soil Series (Site Number)	Horizon	Depth	CEC	ESP	Exchangeable acidity
		--cm--	cmol	%	
		Udic			
		Humid-wet			
Bosville (1)	Ap	0-13			8.1
	E	13-28			4.9
	Bt1	28-53			17.9
	Bt2	53-76			16.5
	Bty3	76-130			10.6
	Bty4	130-168	16	11	6.9
	BC	168-200	16	16	6.9
Dwight (2)	Ap	0-17	-	-	6.13
	Bn1	17-36	-	-	6.62
	Bn2	36-64	-	-	6.49
	Bt3	64-110	21	16	4.04
	Bt4	110-140	-	-	4.17
	BC	140-170+	-	-	4.41
Wing (3)	Ap	0-20			8.3
	Bt1	20-41	16	16	10.8
	Bty2	41-72			8.4
	2Btk3	72-115			6.0
	2BCk	115-170+			3.5
Wister (4)	Ap	0-14			9.1
	E	14-25			12.0
	Bt1	25-55			25.4
	Bt2	55-78			19.5
	Bt3	78-105			14.4
	Cr	105-152+			12.3
Lafe (6)	Ap	0-12			7.9
	Btn1	12-30			3.7
	Bty2	30-55			1.8
	Btk3	55-95			3.3
	BCk	95-140	16	40	2.6
	2Cr	140-170			2.9
	2Cr2	170-195			2.8

TABLE 2.17, cont'd

Soil Series (Site Number)	Horizon	Depth	CEC	ESP	Exchangeable acidity
		--cm--	cmol	%	
		Humid			
Carytown (7)*	Ap	0-6	8.3	14	6.0
	E	6-22	8.2	8	6.0
	Bt1	22-49	25.1	14	9.5
	Bt2	49-89	20.7	12	9.1
	Bty3	89-119	22.4	13	5.5
	Bty4	119-150	23.3	14	4.3
	Bty5	150-193+	21.3	12	2.9
Dwight (8)	Btk2	61-105	32.5	33	-
		Subhumid-humid			
Carytown (15)	Btnk5	138-172	23	61	
		<u>Udic ustic</u>			
		Humid			
Dwight (11)	Btn2	38-67	28	41	
	Bt3	67-95	nd#	46	
		Subhumid-humid			
Pawhuska (5)	Bn1	23-55	29	17	
Pawhuska (5)*	Ap	0-23	13.9	8	5.0
	Bn1	23-55	29.2	14	1.2
	Bty2	55-81	24.9	11	
	Btk3	81-120	24.8	24	2.4
	Bt4	120-150	24.8	22	2.2
	BC	150-210	26.2	18	2.7
Doolin (9)*	Ap	0-23	11.8	11	3.1
	Btn1	23-56	33.4	17	3.0
	Btk2	56-81	29.8	19	
	Btky3	81-107	27.6	15	1.1
	Btk4	107-160	27.3	21	
	2BCk	160-210	23.4	18	
Doolin (14)	Btkn3	69-92	21	21	
	Btknyq4	92-136	nd#	41	
Hinkle (23)	BCk	157-200	19	43	
		Subhumid			
Drummond (12)	A1, b	40-56	20	38	
Oscar (18)	Btn3	78-110	14	70	

TABLE 2.17, cont'd

Soil Series (Site Number)	Horizon	Depth	CEC	ESP	Exchangeable acidity
		--cm--	cmol	%	
		Typic ustic			
Foard (20)*	A	0-10	14.9		3.9
	Btn1	10-32	36.0	16	
	Btnky2	32-60	33.6	18	
	Btnky3	60-90	34.0	15	1.8
	Btkny4	90-122	35.4	20	1.4
	2BCk	122-169	33.2	21	
	2Ck	169-209	37.2	21	
Hinkle 22	Ap	0-18	13.7	9	4.8
	Btkn1	18-41	31.7	26	1.3
	Btkyn2	41-58	27.3	20	1.4
	Btkn3	58-77	25.4	22	0.9
	Btkn4	77-107	20.7	25	0.9
	Btkn5	107-157	14.2	25	
	BCk	157-200	14.0	31	

* - data from National Survey Center,
# - nd=not determined

Physical Properties. The bulk density in all soils sampled sharply increases in the upper B-horizon, with the maximum usually below this (Table 2.18). The consistency of these horizons is firm or hard in all soils. All but the Wister soil have dispersive horizons (dispersion more than 30 %) at some depth in the profile, with most soils of the udic group having dispersion of more than 30% deeper in the profile than soils of the udic ustic and typic ustic groups. Percent dispersion in this study was found to be directly related to SAR and inversely related to EC, gypsum and carbonates presence, and mineralogy (Carter et al., 2000) and hence may be climate dependent. Factors that modify dispersivity of the soil may affect soil structure and siltans formation. Absence of prisms and siltans in soils of the humid –wet subgroup of the udic group may be explained by high acidity values (Table 2.17) and/or high kaolinite content (discussed below), which make these soils insensitive to changes in sodium content (Frenkel at al., 1978; Knodel, 1991; Sumner, 1995; Levy, 2000).

Dispersion may be one of the parameters useful in diagnosis and classification of sodic soils. Dispersion is a characteristic feature of sodic soils, which sometimes may be high (>30%) when SAR is less than 13. Such soils (e. g. Bosville soil series) will be classified as non-sodic, which will affect land use decisions resulting in damage and costly maintenance to structures built from the soils.

Clay Mineralogy. Soils of the humid-wet subgroup of the udic group have more kaolinite and vermiculite than soils of the udic ustic and typic ustic groups in which interstratified smectite –illite mineral dominates (Table 2.19). These data are not in concert with the data of Allen and Hajek (1989) and Borchardt (1989) who reported smectite as a common mineral in sodic soils and the data of Munn and Boehm (1983)

TABLE 2.18

BULK DENSITY AND DISPERSION OF SOILS STUDIED

Soil series (site number)	Bulk Density					Dispersion	
	A-horizon*	B-horizon[#] upper	B-horizon[#] middle	B-horizon[#] lower	C-horizon	%	depth, cm
	----------g/cm³----------						
Udic							
Humid-wet							
Bosville	1.23; 1.64	1.71	1.80..1.88	1.84	1.79	>30	76+
Dwight	1.66	1.73	1.82...1.83	1.7	1.71	>30	17+
Wing	1.59	1.92	1.95	1.77	1.83	>30	20+
Wister	1.59, 1.58	1.54	1.76	1.88	2.08	6-22	25-105
Lafe	1.81	1.92	1.84	1.93	1.72-1.98	>30	55-140
Humid							
Carytown (7)	1.33[#]	1.53	1.79..1.52	1.20	-	30.6	89-119
Dwight (8)	1.10	1.51	1.15	1.24	0.86	>30	19-193
Subhumid-humid							
Carytown (15)	1.41	1.79	1.94..1.85	1.86	1.90	>30	19+
<u>Udic ustic</u>							
Humid							
Dwight (11)	nd	1.41	nd	nd	1.76	>30	13-95
Subhumid-humid							
Pawhuska (5)	1.59	1.51	1.69..1.58	1.72	1.53	>30	82-210
Doolin (9)	nd	1.71	1.92..1.94	2.00	1.85	>30	23-56, 160-210
Doolin (14)	1.61	1.78	1.91..1.52	1.78	-	>30	24-69, 92-166
Seminole (16)	1.44; 1.61[&]	1.88	1.85	1.87	1.98	>30	57-97
Healdton (17)	1.57	1.82	1.89..1.83	2.06	1.94..2.11[$]	>30	13-56, 56-186
Hinkle (23)	1.58	1.90		1.94	2.08..1.90	>30	18-104
Subhumid							
Drummond (10)	1.72	1.79	1.82	1.82	-	>30	26-164
Drummond (12)[a]	1.63	1.72	1.88	1.62	-	>30	40-148
Wing (18)	1.55..1.61	1.92	1.97	1.99	1.86..2.32	>30	27-137
Oscar (19)	1.76	1.86	1.60..1.99	1.92	1.88	>30	15-73
<u>Typic ustic</u>							
Foard (20)	1.69	1.78	1.79..1.78	1.74	1.65..1.92	>30	10-32
Oscar (21)	1.63	1.73	1.89..1.83	1.86	1.83..1.80	>30	9-25, 37-144
Hinkle (22)	1.62	1.78	1.79..1.84	1.62	1.73	>30	18-41, 58-200

* - number after semicolon stands for bulk density in E-horizon, nd- not determined

[&] - second value is for BAn horizon

[a] - data for buried soil

TABLE 2.19

MINERALOGY OF THE SELECTED PROFILES UNDER STUDY

Horizon	Depth	Relative abundances#					
		Kaolinite	Illite	Vermiculite	Quartz	Smectite	Mixed¶
	cm	-----	-----	-----	%	-----	-----
			<u>Udic</u>				
			Humid-wet				
			Bosville (1)				
Bty4	130-168	20	16	-	4	-	60
BC	168-200	27	19	-	4	-	50
			Dwight (2)				
Bt3	64-110	10	5	-	3	-	82
			Wing (3)				
Ap	0-20	47	12	35	4	2	-
Bt1	20-41	44	10	43	3	-	-
Bty2	41-72	54	6	33	4	3	-
2Btk3	72-115	16	5	77	1	1	-
2BCk	115-170+	14	8	76	1	1	-
			Wister (4)	-			
Ap	0-14	72	13	10	5	-	-
E	14-25	49	9	37	4	1	-
Bt1	25-55	18	6	72	1	-	3¶
Bt2	55-78	40	9	46	2	3	-
Bt3	78-105	41	9	43	2	4	-
Cr	105-152+	26	60	8	4	2	-
Pockets*		58	16	21	4	1	-

TABLE 2.19, cont'd

Horizon	Depth	Relative abundances#					
		Kaolinite	Illite	Vermiculite	Quartz	Smectite	Mixed
	cm	--------------	--------------	-------------- %	--------------	--------------	--------------
			Lafe (6)				
Ap	0-12	40	30	18	3	9	-
Btn1	12-30	62	8	16	3	11	-
Bty2	30-55	33	4	60	3	0	-
Btky3	55-95	38	16	30	2	14	-
BCk	95-140	47	13	-	1	-	39¶
2Cr1	140-170	61	26	7	4	2	-
2Cr2	170-195	42	28	22	4	4	-
			Humid				
			Carytown (7)				
Btn1	22-49	13	5	12	-	-	70
			Dwight (8)				
Btk2	61-105	15	6	4	3	-	72
			Subhumid-humid				
			Carytown (15)				
Btnk5	138-172	3	27	60	7	2	1
			Udic ustic				
			Humid				
			Dwight (11)				
Btn2	38-67	9	6	-	3	-	82
Bt3	67-95	6	9	-	3	-	82

TABLE 2.19, cont'd

Horizon	Depth	Relative abundances#					
		Kaolinite	Illite	Vermiculite	Quartz	Smectite	Mixed
	cm	%					
		Subhumid-humid					
		Pawhuska (5)					
Bn1	23-55	5	8	4	10	-	73
		Doolin (14)					
Btkn3	69-92	7	4	14	1	-	74
Btnqy4	92-136	41	15	3	5	-	36
		Subhumid					
		Drummond (12)					
A1, b	40-56	6	56	1	6	-	31
		Oscar (19)					
Btn3	78-110	21	18	-	5	-	56
		Typic ustic					
		Hinkle (22)					
Ap	0-18	5	12	-	5	78	-
Btkn1	18-41	3	6	-	3	88	-
Btnky2	41-58	3	4	-	1	85	7†
Btkn3	58-77	4	7	-	2	-	87†
Btkn4	77-107	4	4	-	2	-	90†
Btkn5	107-157	4	6	-	2	88	-
BCk	157-200	6	28	-	3	-	63†

- percentages estimated from areas of diagnostic x-ray peaks
¶ - randomly interstratified illite-smectite mineral
† - regularly interstratified ilite-smectite mineral
* - pockets of Bt3 material in Cr horizon

who reported the presence of high amounts of smectite in lower portion of the profiles in sodic soils of Northern Montana with smaller more diffused peaks of the mineral in the top two layers. Formation of kaolinite and vermiculite in humid climates is supported by Douglas (1989), Dixon (1989), and Allen and Hajek (1989). Smectite is found in high quantities only in the Hinkle soil (Site 22) of the typic ustic group with traces of smectite in other profiles. This finding supports data of Nettleton and Brasher (1983) who recorded smectite as a dominant clay mineral in most of the argillic and natric horizons of Aridisols and Mollisols of the western U.S. Some increase in smectite (Table 2.19) is recorded in the Lafe soil, which a has high water table. Allen and Hajek (1989) and Borchardt (1989) also found that smectite was common in soils with restricted drainage in the lowest position. Douglas (1989), Dixon (1989), and Birkeland (1999) explained the relation between the climate and clay mineralogy via the effect of the former on the rate of leaching, which along with the water chemistry determines clay mineralogy.

The amount of clay minerals in the soil also depends on parent material as in the Wing soil, which has two parts formed from two different parent materials and a sharp change in kaolinite content between these parts (Table 2.19). Allen and Hajek (1989) also reported effect of parent material on soil clay mineralogy. Douglas (1989) showed that smectite and vermiculite are formed by the alteration of micas, which are abundantly present in many rocks and sediments (Fanning et al., 1989).

Knowing the factors that attribute the most to the sodic soil formation and properties will help to clarify sodic soil definitions and to predict their distribution.

Effect of Vegetation on Sodic Soils Properties

Present and native vegetation supported by the sodic soils studied is represented in Table 2.20. Some of the soils of the udic group located in a once forested area have an E-horizon and a more shallow A horizon, while soils of the drier prairie areas (udic ustic and typic ustic groups) do not exhibit zone of eluviation and have an average thicker surface layer (Table 2.21). Presence of forests in eastern Oklahoma slightly before 550 years ago is supported by Albert (1981).

Sodic Soil Classification

Improving Current Classification of Sodic Soils. Definitions and hence classifications of sodic soils across the world are not consistent. Both have been changed significantly in new U.S. and FAO taxonomies. According to Soil Taxonomy (Soil Survey Staff, 1999), soils, which do not meet chemical criteria (SAR more than 13) are not in a sodic class though morphology and physical properties of these soils are those of sodic soils.

This study field classification, based on county soil maps of 22 soils sampled as sodic based on county soil maps (Soil Survey Staff, 1999), yielded only 17 sodic soils (Table 2.22). Disagreement in the field estimate of classification and the one proposed by USDA (Table 2.22) indicates that sodic soils of the udic group are transitional between leached sodic soils. SAR in 5 non-sodic soils was somewhat less than 13 in the first 40 cm of argillic horizon, but reached or bordered this value deeper in the profile

TABLE 2.20

VEGETATION OF SOILS STUDIED

Soil Series (Site nimber)	Vegetation Native	Present
	Udic	
	Humid-wet	
Bosville (1)	oak forest[1]	fescue pasture
Dwight (2)	tall grasses[2]	pasture
Wing (3)	grasses#	pasture
Wister (4)	forest (oak)[1]	pasture
Lafe (6)		fescue pasture
	Subhumid-Humid	
Carytown (7)	forest[1]	native grasses pasture
Dwight (8)	grasses#	fescue, and Bermuda pasture
	Subhumid	
Carytown (15)	prairie grasses[3]	hay meadow
	Udic ustic	
	Humid	
Dwight (11)	grasses[4]	native pasture
	Humid-subhumid	
Pawhuska (5)	grasses#	wheat field
Doolin (9)	grasses#	native range
Doolin (14)	grasses#	native pasture
Seminole (16)	grasses#	native hay meadow
Healdton (17)	salt tolerant grasses[5]	old cultivated native range
Hinkle (23)	tall and mid grasses[6]	fallow wheat field
	Subhumid	
Drummond (10)	grasses[7]	alkali sacatone
Drummond (12)	salt-tolerant grasses[8]	wheat field
Wing (18)	short and mid grasses[9]	old cultivated rangeland
Oscar (19)	mid grasses[9]	short-grass prairie range
	Typic ustic	
Foard (20)	grasses#	
Oscar (21)	salt-tolerant grasses[10]	old cultivated native range
Hinkle (22)	grasses[11]	plowed wheat field

- vegetation assumed
[1] – from Albert (1981)
[2] - from Shingleton (1971)
[3] – from Cole et al. (1977)
[4] - from Boutlier et al. (1979)
[5] - from Moebius and Maxwell (1979)
[6] - from Bogard et al. (1978)
[7] – from Fisher and Swafford, 1976
[8] – from William et al. (1985)
[9] – from Mobley and Ringwald (1979)
[10] -- from Lamar and Rhodes (1974)
[11] - from Lamar (1979)

TABLE 2.21

DEPTH OF A-, AB-, AND E-HORIZONS IN SOILS STUDIED

Site Number	Horizon Designation	Depth	Total depth to argillic horizon
		----------------cm----------------	
	<u>Udic</u>		
	Humid-wet		
Bosville (1)	Ap	13	
	E	15	28
Dwight (2)	Ap	17	17
Wing (3)	Ap	20	20
Wister (4)	Ap	14	
	E	11	25
Lafe (6)	Ap	12	12
	Humid		
Carytown (7)	Ap	6	
	E	16	22
Dwight (8)	Ap	19	19
	Subhumid		
Carytown (15)	A	19	19
	<u>Udic ustic</u>		
	Humid		
Dwight (11)	A	13	13
	Subhumid-humid		
Pawhuska (5)	Ap	23	23
Doolin (9)	Ap1	9	
	Ap2	14	23
Doolin (14)	A	24	24
Seminole (16)	A	21	
	BAn	13	34
Healdton (17)	Ap	13	13
Hinkle (23)	Ap	18	18
	Subhumid		
Drummond (10)	Ap	26	26
Drummond (12)*	A1, b	16	16
Wing (18)	Ap1	13	
	Ap2	14	27
Oscar (19)	Ap	15	15
	<u>Typic ustic</u>		
Foard (20)	Ap	10	10
Oscar (21)	Ap	9	9
Hinkle (22)	Ap	18	18

* - data for buried soil

TABLE 2.22

FIELD CLASSIFICATION OF STUDIED SODIC SOILS OF OKLAHOMA

Site number	Sampled as[§] Soil Series	Sampled as[§] Taxonomic classification	Taxonomic classification based on data from the study	Soil Series[#]
		Udic		
		Humid-wet		
1	Bosville	Fine, mixed, thermic Albaquic Paleudalfs	Fine, mixed, thermic Albaquic Hapludalf	Cadeville
2	Dwight	Fine, smectitic, mesic Typic Natrustolls	Fine-silty, mixed, thermic Aquollic Hapludalf	nks
3	Wing	Fine, mixed, thermic Aquic Natrustalfs	Fine, kaolinitic, thermic Typic Natrudalf	
4	Wister	Fine, mixed, thermic Vertic Natrudalfs	Very fine, vermiculitic, thermic Typic Hapludalf	
6	Lafe	Fine-silty, mixed, thermic Glossic Natrudalfs	Fine, mixed, thermic Glossaquic Natrudalf	
		Humid		
7	Carytown	Fine, mixed, thermic Albic Natraqualfs	Fine, mixed, thermic Albaquic Paleudalf	Counts
8	Dwight	Fine, smectitic, mesic Typic Natrustolls	Fine-silty, mixed, thermic Pachic Argiudoll	Mason
		Subhumid-humid		
15	Carytown	Fine, mixed, thermic Albic Natraqualfs	Fine, vermiculitic, thermic Typic Natrudoll	nks
		Udic ustic		
		Humid		
11	Dwight	Fine, smectitic, mesic Typic Natrustolls	Fine, mixed, thermic Typic Natrustoll	nks
		Subhumid-humid		
5	Pawhuska	Fine, mixed, thermic Mollic Natrustalfs	Fine, mixed, thermic Typic Natrustalf	nks
9	Doolin	Fine, smectitic, thermic Typic Natrustolls	Fine, mixed*, thermic Typic Natrustalf	nks
14	Doolin	Fine, smectitic, thermic Typic Natrustolls	Fine, smectitic*, thermic Typic Natrustolls	Doolin
16	Seminole	Fine, mixed, thermic Typic Natrustoll	Fine, mixed*, thermic Typic Natrustoll	Seminole[$]
17	Healdton	Fine, mixed, thermic Vertic Natraqualfs	Fine, mixed*, thermic Typic Natrustalf	nks
23	Hinkle	Fine, smectitic, thermic Vertic Natrustalfs	Fine-silty, mixed*, thermic Typic Natrustalf	Oscar[&]
		Subhumid		
12	Drummond	Fine, mixed, thermic Mollic Natrustalfs	Fine-silty, mixed, thermic Typic Natrustoll	nks
10	Drummond	Fine, mixed, thermic Mollic Natrustalfs	Fine, mixed*, thermic Vertic Natrustoll	nks

Table 2.22, cont'd

Site number	Sampled as[§]		Taxonomic classification based on data from the study	Soil Series[#]
	Soil Series	Taxonomic classification*		
18	Wing	Fine, mixed, thermic Aquic Natrustalfs	Fine-loamy, mixed, thermic Typic Natrustalf	nks
19	Oscar	Fine-silty, mixed, thermic Typic Natrustalfs	Fine-loamy, mixed, thermic Typic Natrustalf	nks
		Typic ustic		
20	Foard	Fine, smectitic, thermic Vertic Natrustolls	Fine, mixed*, thermic Leptic Natrustalf	nks
21	Oscar	Fine-silty, mixed, thermic Typic Natrustalfs	Fine-silty, mixed*, thermic Typic Natrustalf	Oscar
22	Hinkle	Fine, smectitic, thermic Vertic Natrustalfs	Fine, smectitic, thermic Typic Natrustoll	nks

[§] - USDA/NRCS classification
[#] - nks – no known series
[$] - The soil is Seminole if lower B had 35-50% clay
[&]- The soil is Oscar if C had 24-35% clay
* - Mineralogy class is assumed

(Table 2.23). Soil of the Bosville series from the humid-wet subgroup of the udic group that carry properties of sodic soils has been mapped by NRCS/USDA as non-sodic.

Soils presented in Table 2.23 should be recognized as sodic at a subgroup level for Alfisols and Mollisols. The proposed revised classification (this study) for these soils is presented in Table 2.24. Soils with SAR of more than 13 within 1 meter of the soil mineral surface are placed in a *natric* subgroup (the Dwight soil, site 8), soils with SAR in a range between 4 and 13 (corresponds to the ESP range of 6 to 15%) within 2 m of the soil mineral surface and having E-horizon are placed in a *solodic* subgroup (the Bosville, Wister, and Carytown soils, sites 1, 4, and 7, respectively), and soils with SAR in a range between 4 and 13 within 1 m of the soil mineral surface are in a *sodic* subgroup (the Dwight soil, site 2). The solodic subgroup is named due to a resemblance of these soils to Solods (leached sodic soils) and is distinguished as a separate order or type in modern Canadian (Agriculture Canada Expert Committee on Soil Survey, 1987) and Russian (Kaurichev, 1989) soil classifications, respectively. *Sodic* and *natric* subgroups are present in some great groups of Aridisol, Entisol, Inseptisol, and Vertisol orders and in Vermaqualf, Haploxeralf, and Palexeralf great groups (Soil Survey Staff, 1999) and *endosodic* subunit is used in FAO classifications (FAO, 1998) to include soils with SAR values within a range of 6 to 13 within 40 or 100 cm of the mineral soil surface. Bakhtar (1973) reported soils in north central Oklahoma with $6 \leq ESP \leq 15$ that may be a transition between sodic (Natrustolls) and nonsodic (Argiustolls) and suggested a new subgroup – *nazdic*, which means near sodic. Seelig et al. (1991) suggested classifying leached soils associated with Natraquolls and currently defined as Typic Argiaquolls as Solods. Seelig and Richardson (1994) recognized these soils as a new subgroup, Natraquic Argiaquolls,

TABLE 2.23

SUBSOIL SAR VALUES IN SOILS CLASSIFIED AS NON-SODIC

Soil series Site number	Horizon	Depth	SAR
		--cm--	
	<u>Udic</u>		
	Humid-wet		
Bosville	Bt1	28-53	1.6
Site 1	Bt2	53-76	5.1
	Bty3	76-130	4.6
	Bty4	130-168	7.7
	BC	168-200	11.8
Dwight	Bn1	17-36	4.9
Site 2	Bn2	36-64	8.7
	Bt3	64-110	11.4
	Bt4	110-140	10.8
	BC	140-170	12.1
Wister	Bt1	25-55	3.1
	Bt2	55-78	4.6
	Bt3	78-105	11.7
	Cr	105-152	15.3
	Humid		
Carytown	Btn1	22-49	10.0
Site 7	Bt2	49-89	9.9
	Bty3	89-119	10.0
	Bty4	119-150	9.9
	Bty5	150-193	8.2
Dwight	Bn1	19-61	10.7
Site 8	Btk2	61-105	22.8
	Btk3	105-152	23.4
	BCk	152-193	18.6

TABLE 2.24

PROPOSED CLASSIFICATION OF SODIC SOILS OF OKLAHOMA

Soil Series (Site number)	Field classification*	Proposed Classification
	<u>Udic</u>	
	Humid-wet	
Bosville (1)	Albaquic Hapludalf	Solodic Hapludalf
Dwight (2)	Aquollic Hapludalf	Sodic Hapludalf
Wing (3)	Typic Natrudalf	Typic Natrudalf
Wister (4)	Typic Hapludalf	Solodic Hapludalf
Lafe (6)	Glossaquic Natrudalf	Saline Natrudalf
	Humid	
Carytown (7)	Albaquic Paleudalf	Solodic Paleudalf
Dwight (8)	Pachic Argiudoll	Natric Argiudoll
	Subhumid-humid	
Carytown (15)	Typic Natrudoll	Saline Natrudoll
	<u>Udic ustic</u>	
	Humid	
Dwight (11)	Typic Natrustoll	Typic Natrustoll
	Subhumid-humid	
Pawhuska (5)	Typic Natrustalf	Nonsaline Natrustalf
Doolin (9)	Typic Natrustalf	Nonsaline Natrustalf
Doolin (14)	Typic Natrustoll	Typic Natrustoll
Seminole (16)	Typic Natrustoll	Nonsaline Natrustoll
Healdton (17)	Typic Natrustalf	Typic Natrustalf
Hinkle (23)	Typic Natrustalf	Saline Natrustalf
	Subhumid	
Drummond (10)	Vertic Natrustoll	Saline Natrustoll
Drummond (12)	Typic Natrustoll	Saline Natrustoll
Wing (18)	Typic Natrustalf	Saline Natrustalf
Oscar (19)	Typic Natrustalf	Saline Natrustalf
	<u>Typic ustic</u>	
Foard (20)	Leptic Natrustalf	Saline Natrustalf
Oscar (21)	Typic Natrustalf	Salic Natrustalf
Hinkle (22)	Typic Natrustoll	Saline Natrustoll

* - based on Soil Taxonomy (Soil Survey Staff, 1999)

intergrade between Natraquolls and Argiaquolls. Edmonds et al. (1986) proposed to broaden the definition of morphological properties of the natric horizon and to include soils with SAR >13 and blocky structure into Natric great groups.

All soils of the udic ustic and typic ustic groups and three soils (the Wing, Lafe and Carytown soils) of the udic group were classified as sodic (Natrudolls, Natrudalfs, Natrustolls or Natrusalfs) in this study and by NRCS/USDA (Table 2.22). Further classification of such soils should include properties that reflect moisture conditions in the soils. Salinity as affected by evaporation and leaching processes may be a good criterion to differentiate between soils with different moisture regime and drainage. Soils are placed in a *nonsaline* subgroup if an EC in the natric horizon (SAR≥13)is less than 2, in *typic* subgroup if EC is between 2 and 4, in a *saline* subgroup if an EC is more than 4, and in a *salic* subgroup if an EC is more than 15 (Table 2.24).

Distribution of the Proposed Sodic Soil Groups. Each subgroup from Table 2.24 is characterized by certain geographic location along the P-E index gradient (Table 2.25). There is also variability inside the region with certain climatic conditions, which depends on parent material, ground water composition, and drainage conditions. Impeded drainage and shallow saline ground water in the humid-wet climate subgroup of the udic group accounted for the development of sodic soils (great group of Natrudalf) along with leached sodic soils (solodic, natric or sodic subgroups of soils of other great groups), with the latter being more widespread in the region with the highest P-E index (Table 2.25). In contrast, saline and salic subgroups cover large areas in regions with a lowest P-E index. Variability in sodic soil distribution may be attributed also to parent material, presence of

TABLE 2.25

DISTRIBUTION OF THE PROPOSED SODIC SOIL GROUPS IN OKLAHOMA

Soil Groups	NRCS/USDA Soil Series	Location*	MAP# range cm	LEVAP$ range cm	MAT¶ range C°	Mean P-E Index	Area covered
Solodic Hapludalf	Wister, Bosville	Southeast	112-122	122-132	16-17	95, 99	small
Sodic Hapludalf	Dwight	East Central	112	122-132	16-17	92	small
Typic Natrudalf	Wing	South East	112-122	122-132	16-17	99	small
Saline Natrudalf	Lafe	East Central	112-122	122-132	16-17	97	small
Solodic Paleudalf	Carytown	East Central	102-112	122-132	16-17	86	small
Natric Argiudoll	Dwight	East Central	102	122-132	16-17	89	small
Saline Natrudoll	Carytown	North East	91-102	122-132	16-17	74	small and large
Nonsaline Natrustoll	Seminole	Central	91	122-132	16-17	75	small
Typic Natrustoll	Dwight,	Northeast	91-102	132	14-16	90	small
	Doolin	Central	81-91	132-142	16-17	71	small
Nonsaline Natrustalf	Pawhuska,	Central	81-91	142	16-17	67	small
	Doolin	Central	81-91	142	16-17	67	small
Typic Natrustalf	Healdton	South Central	81-91	132-142	16-17	70	small
Saline Natrustoll	Drummond,	Central	71-81	142-152	16-17	63	small
	Drummond	North Central	71-81	142-152	14-16	62	small
	Hinkle	Southwest	71-81	142-152	16-17	66	small
Saline Natrustalf	Wing, Oscar,	South Central	81-91	142-152	16-17+	54	large, small
	Hinkle	Central	81-91	142-152	16-17	67	small
Halic Natrustalf	Oscar	Southwest	71-81	152	16-17+	57	large
Leptic Natrustalf	Foard	Southwest	71-81	152	16-17+	59	large

* - from: Oklahoma Climatological Survey, http://radar.ou.edu/ocs/climmo/index.html

¶ - MAT – mean annual temperature

- MAP - mean annual precipitation

$ - LEVAP – estimated annual lake evaporation a shallow water table, properties of surrounding bedrock, which determine ground water composition, and local geologic and hydrologic conditions of the area.

Conclusions

There is a gradual change in sodic soils properties along the P-E index and soil moisture regime gradients. Depth and value of salinity (EC), depth to carbonates, depth and values of maximum relative sodium content and SAR, and pH increased with decreasing mean annual precipitation and annual lake evaporation (decreasing P-E index). Clay mineralogy of sodic soils studied showed climate dependence. Predominant clay minerals in soils of the humid-wet subgroup of the udic group are kaolinite and vermiculite; in soils of udic ustic and typic ustic groups it is interstratified smectite-illite. Soils of the udic group in the forested eastern part of the state had an elluviation horizon and a thinner and lighter-colored A horizon compared to soils of the udic ustic and typic ustic groups on the west. Variability of sodic soils on a local scale was affected by position on the landscape, which influences presence of water table close to the surface. Parent material affected soil occurrence, as well as soil color, texture, chemical composition of soil water solution, and clay mineralogy. The presence of a ground water with relatively large sodium content determines the occurrence of sodic soils in the area.

Suggested classification for sodic soils in Oklahoma takes into account soil salinity, which differs significantly between soils with different moisture regimes and landscape positions and is recognized on a subgroup level. For sodic soils (natric great groups of Mollisols and Alfisols) subgroup name reflects the electrical conductivity value of a saturated paste: non-saline ($EC<2$), typic ($2 \leq EC<4$), saline ($4<EC<15$), and salic ($EC>15$). Soils of the udic group show a more advanced stage in Solonetz soils development and require reconsideration of their classification criteria. These soils should be recognized as sodic soils at least on a subgroup level, namely solodic Hapludalfs.

CHAPTER III

GENESIS AND CLASSIFICATION OF SODIC SOILS UNDER HUMID CONDITIONS OF SOUTHEAST OKLAHOMA

Abstract

Little information can be found for sodic soils in subhumid and humid regions. This study analyzes selected sodic and "leached" sodic (Solods) soil morphological and chemical properties to reveal sodic soil patterns on the landscapes of the humid part of Oklahoma. Five soil profiles were sampled in the southeast part of Oklahoma. Each soil profile was described in the field and characterized in the laboratory. Hypothetic toposequence of three types of sodic soils based on field description and chemical characterization data is suggested. The first type, soils with SAR of more than 13 and salinity values reaching 4 and more dS/m within upper 40 cm of the argillic horizon, are located in alluvium in the lowest position on a landscape and have a shallow water table for most of the year. The second type, soils with SAR reaching values of 6 and higher within 100 cm of the soil surface and low salinity ($EC \leq 2$ dS/m), which can be found in alluvium on upper terraces. The third type of sodic soils, "leached sodic soils," are characterized by presence of E-horizon, SAR reaching values of 6 and higher within 2 m of the soil mineral surface and low salinity. These soils are formed on uplands or in alluvium on the upper terrace.

Introduction

Sodic soils are salt affected soils with a large sodium content on the soil cation exchange complex and in the soil solution. The presence of sodium exerts a strong effect on soil structure and dispersion.

The first theory of Solonetz origin was proposed by de Sigmond (1926) and Gedroiz (1927) and has been supported by a number of authors (Kellog, 1934; Kelley, 1934; Murphy and Daniel, 1935; MacGregor and Wyatt, 1945; Bentley and Rost, 1947; Kelley, 1951; Westin, 1953; Wittig and Janitzky, 1967; Arshad and Pawluk, 1966; Fullerton and Pawluk, 1987; Hopkins et al, 1991; Miller and Pawluk, 1994; Seelig and Richardson, 1994). The theory requires the presence of a water table, either permanent or ephemeral, close enough to the soil surface to be affected by evapotranspiration, with a consequent upward convective movement of sodium, an arid or semiarid climate,and periods of temporary excessive moisture interspersed with dry periods. The theory views Solonetz soils as one stage in the evolution of the alkali soils that may be summarized as follows:

Normal soils. The soils that are not salt effected. In these soils the base exchange is saturated with divalent cations (Ca, Mg), the colloids are flocculated and the soil is easy to till and its permeability is good.

Solonchak. Soil with accumulated sodium rich salts originating from (1) sedimentary rocks deposited by sea or salt lake, (2) atmospheric dust or precipitation, (3) irrigation water, (4) saline ground water, (5) volcanic activity, and (6) biological activity. In general, Solonchaks are found in places where the ground water is close enough to the surface table (usually less than 3 m in dry season), or has been in previous times as to permit rise by capillarity of water together with dissolved salts into the top soil where evaporation takes place. The process of salt accumulation in soil is called *salinization*. (*Alkalinization* is the replacing of divalent cations on soil exchange complex of saline soils by monovalent cations, especially sodium).

Solonetz (nonsaline alkali, leached alkali). Soil that previously contained an excess of sodium salts. These soils have a relatively high percentage of exchangeable sodium and a low percentage of soluble salts (chemical properties of the Solonetz). This is the result of natural leaching of soluble salts (*solonization*) after the water table has receded sufficiently for leaching to be effective. Such soil usually has columnar structure and bleached sand and silt grains that form siltans along the ped faces. Such an appearance is often called "solonetz morphology."

Solod (degraded alkali). Solonetz soils are comparatively rapidly leached even in a relatively arid climate. Upon continued leaching, exchangeable hydrogen increases and soil pH lowers. The amorphous SiO_2 released by decomposition is believed to remain largely in the upper part of the soil profile; some of SiO_2 accumulates as a light-colored coating (siltans) on or around the tops of peds. The process is called *solodization* and results in "degraded soil" (soil with mostly hydrogen on the cation exchange complex). Solods often have an E-horizon – zone of elluviation. The profile of these soils may still exhibit solonetz morphology.

Other research studies stressed the role of factors other than the presence of a water table. Some pointed out the significance of lateral moisture movement (Lewis et al., 1959; Wilding et al., 1963; Munn and Boehm, 1983; Johnson et al., 1985; Reid et al., 1993). Other studies have concluded that a natric horizon formed through deposition of dust of large salt content from nearby playas (Ballantyne, 1978; Peterson, 1980; Reid et al., 1993). After deposition, the salts and the clay from the dust were moved downward and accumulated in a subsoil to form a natric horizon. The effect of irrigation waters on the development of alkali soils was pointed out by several scientists (Hilgard, 1918; Harper and Stout, 1950; Reed, 1962; Levy, 2000). Land management practices that can lead to waterlogging, such as forest clearing, produce sodic soils (Levy, 2000).

Most papers on sodic soil genesis consider the formation in arid and semi-arid climates, where sodic soils are widespread. Little information can be found about soils with high sodium content in humid regions. Smith (1937) attributed the occurrence of Solonetz-like soils under humid conditions in Illinois to an accumulation of bases by means of lateral water movement along relatively impervious substrata and by interruption of leaching, either by an impervious substrata or by a high water table.

In Oklahoma, soils with a large content of sodium can be found under a wide range of mean annual precipitation from 71 to 122 cm and an annual lake evaporation of 163-122 cm. A few studies of sodic soil genesis in the relatively dry central part of Oklahoma have been done (Bakhtar, 1973; Mutter, 1982).

In this study, the objective was to analyze selected major types of sodic and leached sodic (Solods) soils to reveal the formation pathways. Based on the information collected in the field and in laboratory studies, a hypothetical sequence of events resulting in formation of sodic and leached sodic soils in eastern Oklahoma is proposed.

Materials and Methods

Description of the Study Area

Five typical examples of sodic soils were sampled July 1997 in southeast part of Oklahoma, in the counties of Choctaw, Pittsburgh, Sequoyah, and Le Flore (Fig. 3.1). General geology of Choctaw County is nonmarine sand and clay and marine limestone and clay of Cretaceous age. Le Flore, Pittsburgh, and Sequoyah counties have dominantly marine shale with interbedded sandstone and limestone of Pennsylvanian age (Branson and Johnson, 1979). These counties are coal-producing areas (Moose and Suarle, 1929). The climate of the region is continental with a mean annual temperature of 16 °C, a mean annual precipitation of 112-122 cm, and an estimated annual lake evaporation of 122-132 cm (Johnson and Duchon, 1995). The area studied has a udic soil moisture regime (Soil Survey Quality Assurance Staff, 1994). The Precipitation-Evaporation (P-E) index was calculated by the following equation suggested by Thorntwaite(1931):

$$\text{P-I index} = \sum_{n=1}^{12} 115 * (P/(T-10))_n^{\frac{9}{10}},$$

where P – is precipitation in inches, T – is temperature in F°. Precipitation and temperature data for ten consecutive years where taken from 4 Oklahoma weather stations (National Oceanic and Atmospheric Administration, 1989-1999) located close to sites where soils were sampled. The P-E index for the area studied (Fig. 3.1) ranged from 67 to 152. Ground water in the area is of fair quality in general but locally may contain large amounts of total dissolved solids and/or have high SAR values (Dott, 1942; Davis, 1960).

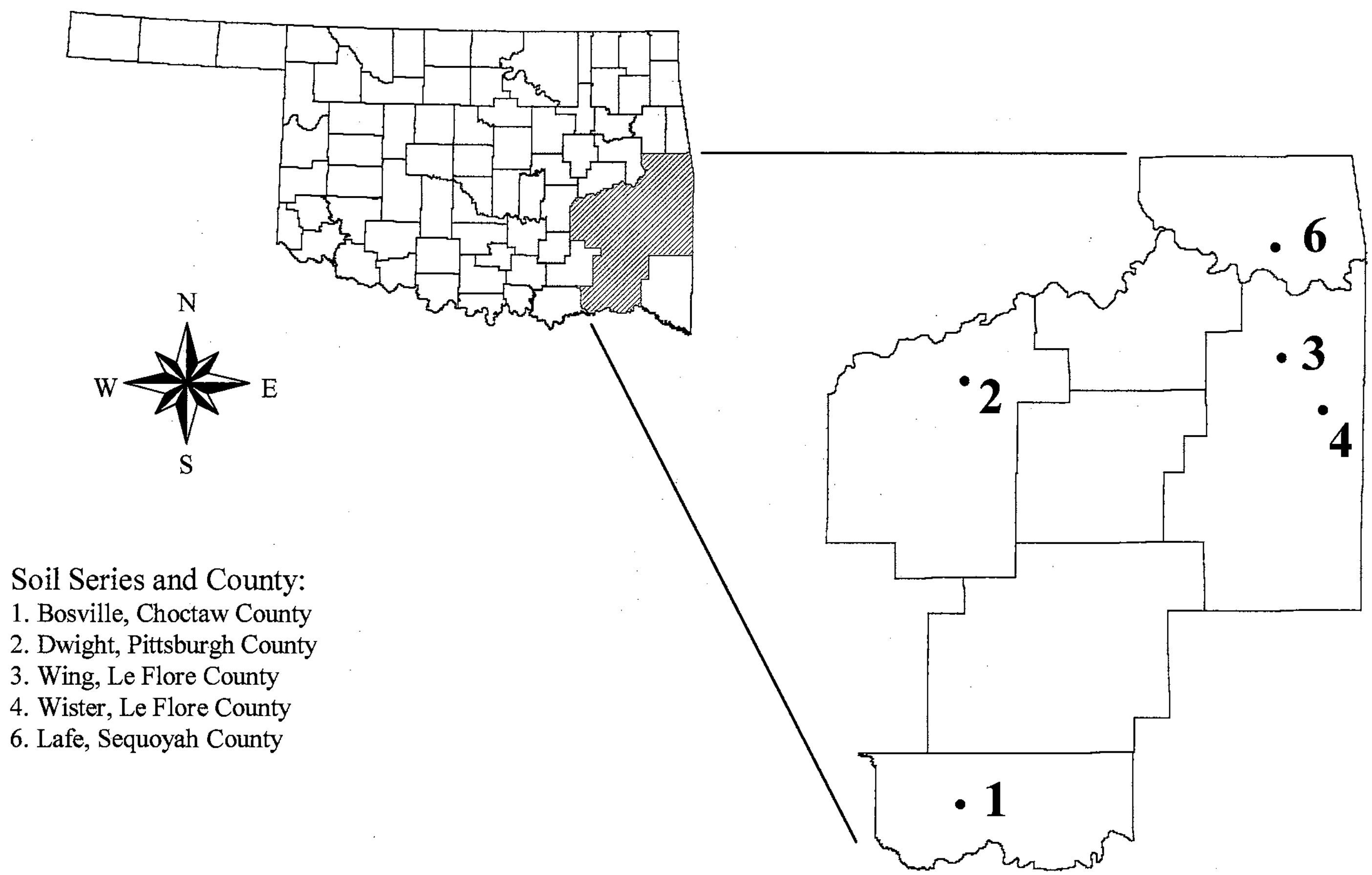

Fig. 3.1. Sampling Locations of Sodic Soils in Eastern Oklahoma

Classifications of profiles sampled inferred by USDA/NRCS (http://www.statlab.iastate.edu/soils/osd/, 1998) and actual classifications are presented in Table 3.1. The soil mapping unit's names and legal descriptions of sites are shown in Table 3.2.

Soil Sampling and Characterization

Soils were described in 2 meters deep T-shaped pits using standard techniques (Soil Survey Division Staff, 1993). Moist soil color and color of redohimorphic features were determined by the Munsell Soil Color Charts (GretagMcbeth, 1994). Soil pH in the field was measured with HELLIGE Soil Reaction pH Tester (Ben Meadows Company). Designation "n," natric, for B-horizons was made based on the presence of prismatic or blocky structure with siltans along the ped faces or on the presence of salt crust in the area.

Characterization of soils was performed in the Department of Plant and Soil Sciences at Oklahoma State University. Pipette method analysis following removal of salts and organic matter (Gee and Bauder, 1986; USDA, NRCS, NSSC, 1996a) was employed to determine particle size distribution. Soil bulk density was measured on saran-coated clods (Blake and Hartge, 1986; USDA, NRCS, NSSC, 1996b). Organic matter content was identified by titration following digestion with an acidified dichromate (Yeomans and Bremner, 1988). Saturation extracts from each horizon were analyzed for pH, electrical conductivity (EC), and selected cations and anions. Soil reaction (pH) in saturated paste extract and in 1:1 soil-water solution by weight was measured with a calibrated

TABLE 3.1

CLASSIFICATION OF THE SODIC SOILS STUDIED IN EASTERN OKLAHOMA

Site number	Sampled as[§]		Taxonomic classification based on data from the study	Soil Series[#]
	Soil Series	Taxonomic classification		
		Udic **Humid-wet**		
1	Bosville	Fine, mixed, thermic Albaquic Paleudalfs	Fine, mixed, thermic Albaquic Hapludalf	Cadeville
2	Dwight	Fine, smectitic, mesic Typic Natrustolls	Fine-silty, mixed, thermic Aquollic Hapludalf	nks
3	Wing	Fine, mixed, thermic Aquic Natrustalfs	Fine, kaolinitic, thermic Typic Natrudalf	nks
4	Wister	Fine, mixed, thermic Vertic Natrudalfs	Very fine, vermiculitic, thermic Typic Hapludalf	nks
6	Lafe	Fine-silty, mixed, thermic Glossic Natrudalfs	Fine, mixed, thermic Glossaquic Natrudalf	nks

[§] - USDA/NRCS classification
[#] - nks – no known series

TABLE 3.2

SITE DESCRIPTIONS OF SAMPLED SOILS

Site No.	Soil mapping unit	County	Legal description	Associated soil series
1	Bosville sandy loam, 4-8% slopes	Choctaw	SE1/4 NW1/4 Sec.20 T6SR15E	Muskogee, Bernow
2	Parsons-Dwight complex, 1-3% slopes, eroded	Pittsburgh	NW1/4 SE1/4 Sec.22 T8NR14E	Dennis, Choteau
3	Wing silt loam, 0-2% slopes	Le Flore	SW1/4 SW1/4 Sec.16 T9N R24E	Wister, Stigler
4	Wister silt loam, 0-1% slopes	Le Flore	SW1/4 NE1/4 Sec.34 T8NR26E	Wing
6	Lafe soils	Sequoyah	NE1/4 NE1/4 Sec. 1 T11NR24E	Stigler, Rosébloom, Ennis

combination electrode/digital pH meter (McLean, 1982; USDA, NRCS, NSSC, 1996c; USDA, NRCS, NSSC, 1996j). A conductivity bridge was employed to measure EC (U.S. Salinity Laboratory, 1954; USDA, NRCS, NSSC, 1996d). Concentrations of Ca, Mg, K, and Na were determined by atomic absorption spectrophotometry (U.S. Salinity Laboratory, 1954; USDA, NRCS, NSSC, 1996e). Carbonate and bicarbonate concentrations were found by titration with the sulfuric acid (USDA, NRCS, NSSC, 1996f). Chloride and sulfate were determined by ion chromatography (USDA, NRCS, NSSC, 1996g). The SAR was calculated from soluble Na, Mg, and Ca concentration using the following equation (U.S. Salinity Laboratory, 1954; USDA, NRCS, NSSC, 1996h):

$$SAR = Na / ((Ca + Mg)/2)^{1/2}$$

Soil extractable acidity was done by leaching soil with a barium chloride-thriethanolamine ($BaCl_2$-TEA) solution buffered at pH=8.2 using a mechanical automatic extractor (Holmgren, 1977) followed by HCl titration (Peech et al, 1947; USDA, NRCS, NSSC, 1996k). X-ray diffraction techniques were used to identify the clay mineralogy of selected soil horizons (Whittig, and Allardice, 1986). The abundance of clay minerals species was estimated from the area of diagnostic x-ray peaks. The Oklahoma Department of Transportation Testing Laboratory provided dispersion characteristics of soils tested with double hydrometer (ASTM Standard D4221, 1990), pinhole (ASTM Standard D4647, 1990), and crumb methods (Emerson, 1954). Horizons were considered dispersive if dispersion identified by the double hydrometer test was greater than 30 % (Knodel, 1991).

The presence of redoxomorphic depletions was determined by presence of gleic colors or colors with high value (≥4) and low chroma (≤2) (Soil Survey Staff, 1999). Black colored concretions and soft bodies were determined as Fe-Mn concretions. Salinity, depth, and acidity classes were determined by using the Soil Survey Manual (Soil Survey Division Staff, 1993).

Results and Discussion

Characterization and Genesis of Sodic Soils

Introduction. The eastern part of Oklahoma has a variety of sodic soils. Retaining sodium in the upper 2 m of a profile in soils of eastern Oklahoma is attributed to the presence of a perched water table at the sites (Table 3.3) coupled with drought periods during the summer (Abernathy, 1970). The presence of sodic soils in humid climates has several explanations. Joffe (1936) suggested that sodic soils are relics of former arid or semi-arid climates. Smith (1937) studied sodic soils in Illinois and found that impeded leaching caused by either a perched water table or a relatively impermeable substratum might contribute to sodic soil genesis in humid regions.

Based on field observations and chemical data, three types of sodic soils were distinguished. The first type includes soils of a Natrudalf great group - the Wing and Lafe soils (sites 3 and 6, respectively). The second type includes soils of a Hapludalf great group represented in this study by the Dwight soil (site 2). Type three also consists

Table 3.3

LANDSCAPE POSITION AND DRAINAGE CHARACTERISTICS OF SOILS UNDER STUDY

Series (site number)	Landscape Position	Slope %	Water table depth	Water table season*	Drainage#	Water table depth at sampling time¶
						---------cm---------
Bosville (1)[1]	high terrace	4-8	perched, 30-60 cm	W, Sp	mod. well	nf
Dwight (2)[2]	high terrace	1-3	NA	NA	mod. well	nf
Wing (3)[3]	low terrace	0-2	perched, 15-30 cm	W, Sp	mod. well	nf
Wister (4)[3]	uplands	0-1	perched, 30-60 cm	W, Sp	mod. well	nf
Lafe (6)[4]	low terrace	0-2	NA	NA	somewhat poor	170 (July)

* - W – winter, Sp – spring
# - mod. – moderately
¶ - nf = not found within 200 cm depth at the time of sampling
[1] – slope and water table data from Swafford and Reasoner (1979)
[2] - slope and water table data from Shingleton (1971)
[3] – slope and water table data from Abernathy et al. (1983)
[4] - slope and water table data from Abernathy (1970)

of soils of a Hapludalf great group and is exemplified by the Bosville and Wister soils (sites 1 and 4 respectively). Each type is discussed in a separate section below.

Type 1 - Natrudalf. Soils of Wing (site 3) and Lafe series (site 6) are the first type of sodic soils that may be encountered in humid areas. According to morphological (Table 3.4) and chemical (Table 3.5) properties, these soils are Natrudalfs (Soil Survey Staff, 1999). These soils have high soluble sodium (SAR values in both profiles are more than 13 in upper 40 cm of argillic horizon), relatively high salinity (EC>2) and pH (>7), and low exchangeable acidity throughout the profile (Table 3.5). Poor drainage evidenced by shallow depth to redoximorphic depletions of the Lafe soil (site 6) attributed to higher values of SAR, EC, pH and lower exchangeable hydrogen compared to the Wing soil (site 3). These soils are also characterized by the highest bulk density value in subsurface compared to the other profiles under study. The Wing soil has dispersive horizons (Table 3.5) owing to high sodium content (Knodel, 1991). The Lafe soil, though having high SAR values, has low dispersion values (< 30%) in upper B-horizon layers most likely due to high soluble salts content which is known to offset dispersion enhanced by high sodium content (Curtin, 1994). The amount of gray colored redoximorphic features increased with depth (Table 3.4) indicating reduced conditions in both profiles. The gley layer at the bottom of the A-horizon in Wing suggests possible ponding at the site due to drastic textural difference between the A and B-horizons (Table 3.4) evidenced also by a quick density increase in the B-horizon (Table 3.5). Color of matrix and redoxomorphic features in the lower B were the main morphologic features that distinguished these profiles from others under study and resulted from lowest position on a landscape (Table 3.4). Seelig et al. (1990a) also stressed the importance of soil color in differentiating

TABLE 3.4

MORPHOLOGY OF THE SAMPLED PROFILES

Horizon	Depth	Color (moist)	Particle size distribution** Sand	Silt	Clay	Class	Structure#	Redox features‡ color	abund	Consis tence§	Roots¶	Boundary†	Siltans	Gypsum&	Carb$	Fe-Mn concr£
	cm		--------------%------------													
								Type 1 - Natrudalf								
								Wing Soil Series (site 3)								
Ap	20	10YR 4/2	17.6	69.1	13.3	sil	1msbk	-	-	fr	2f-m	as	-	-	-	-
Bt1	41	10YR 4/4	9.7	48.3	42.0	c	2mp/ 3msbk	7.5YR5/6	2fd	f	1f	cw	-	-	-	-
Bty2	72	2.5Y 5/4	7.4	44.7	47.9	sic	2msbk	7.5YR 6/8	2fp	f	1f	gs	-	1fpc	-	-
2Btk3	115	10YR 5/4	13.3	40.9	45.6	c	1csbk	N7/0 7.5YR 5/8	2mp 2md	f	-	dw	-	-	1fno	2fcon 2fsb
2BCk	170+	7.5YR 6/8, N 5/0	13.9	42.3	43.6	c	1csbk	mtl		f	-	-	-	-	2fno	-
								Lafe Soil Series (site 6)								
Ap	12	2.5Y 8/4	34.4	47.1	18.3	l	1cpl	-	-	fr	-	as	-	-	-	-
Bn1	30	10YR 6/4	17.2	44.3	38.5	sicl	2c-sbk	N 5/0	1fd							
								10YR 6/8	2md	fr	-	gw	-	-	-	1fno
Bty2	55	2.5Y 5/6	16.6	40.4	42.9	sic	1cpr/									
							2msbk	2.5YR 6/2	1md							
								10YR 5/6	2fd	fr	-	gw	-	1fm	-	1fno
Btky3	95	10YR 6/6	19.9	36.6	43.4	c	2cpr	7.5YR 6/8	2cd							
								10YR 6/1	2cfn	f	-	gw	-	3fm	3fno	1fno
BCk	140	7.5YR 6/8	26.5	34.0	39.5	cl	massive	-	-	f	-	cw	-	-	2fno	-
2Cr	170	10YR 5/1	0.9	66.2	33.0	sicl	massive	-	-	-	-	cs	-	-	-	-
2Cr2	195+	10YR 5/1	3.0	62.7	34.3	sicl	massive	-	-	vf	-	-	-	-	-	1ccon

TABLE 3.4, cont'd

Horizon	Depth	Color (moist)	Particle size distribution** Sand	Silt	Clay	Class	Structure#	Redox features‡ color	abund	Consis tence§	Roots¶	Boundary†	Siltans	Gypsum&	Carb$	Fe-Mn concr£
	cm		-------------%-----------													
								Type 2 – Proposed sodic Hapludalf								
								Dwight Soil Series (site 2)								
Ap	17	10YR 3/2	15.5	62.6	21.5	sil	1m-sbk	-	-	fr	2vf	as	-	-	-	-
Bn1	36	10YR 4/2	9.2	58.0	32.6	sicl	3mpr	10YR 3/2	2ffn	vf	1f	cs	-	-	-	-
Bn2	64	10YR 5/2	8.4	58.5	32.7	sicl	3mpr	10YR 3/2	2fd	vf	1f	cw	common	-	-	-
Bt3	110	10YR 3/2	6.5	56.2	37.0	sicl	1m-sbk	10YR 3/2	2ffn	vf	-	gw	few	-	-	-
Bt4	140	10YR 6/2	3.6	55.2	41.1	sic	1m-sbk	10YR 3/2	2fd							
								10YR 5/8	2fd	vf	krot	cw	-	-	-	-
BC	170+	10YR 6/2	2.2	51.0	46.7	sic	massive	10YR 3/2	2md	vf	krot	-	-	-	-	-
								Type 3 – Proposed Solodic Hapludalf								
								Bosville Soil Series (site 1)								
Ap	13	10YR 5/4	34.9	58.4	6.4	sil	2f-sbk	-	-	vfr	3f-m	cs	-	-	-	-
E	28	10YR 6/3	41.3	51.2	8.7	sil	1m-sbk	7.5YR6/8	2fp	fr	3f-m	cw	-	-	-	-
Bt1	53	10YR 6/6	26.5	29.5	43.6	c	3f-sbk	2.5YR4/8	3mp	vf	2f-m	cs	many	-	-	1fsb
Bt2	76	2.5YR 4/8	23.9	32.3	43.5	c	3cpr/1csbk	N7/0	1fp	vf	1f	aw	common	-	-	-
Bty3	130	10YR 6/6	29.6	38.1	32.0	cl	3csbk	10YR5/8	1fd	vf	1f	gs	common	1fpcth	-	-
Bty4	168	10YR 6/6	33.6	36.1	30.1	cl	2cpr/1csbk	5YR7/2	1cp	vf	1f	cs	common	1fpcth	-	1csb
BC	200+	10YR 6/6	21.9	45.1	32.5	cl	2cpr/1csbk	-	-	vf	1f	-	few	-	-	1csb
								Wister Soil Series (site 4)								
Ap	14	10YR 4/3	17.8	65.8	16.0	sil	1msbk	-	-	fr	2vf-f	cw	-	-	-	-
E	25	10YR 4/4	14.5	62.9	22.5	sil	1msbk	-	-	fr	2vf-f	cw	-	-	-	-
Bt1	55	10YR 4/3	2.7	24.4	72.9	c	2msbk	5 YR3/4	3mfn	f	1f	gw	-	-	-	-
Bt2	78	2.5Y 5/3	3.0	28.2	68.8	c	2msbk	2.5YR 4/8	2cp	f	1f	gw	-	-	-	-
Bt3	105	2.5YR 5/2	5.5	43.6	51.0	sic	1msbk	mtl	-	f	ch	cw	-	-	-	-
		5YR 4/6														
CrΩ	152+	olive shale	5.0	68.7	26.3	sic	massive	-	-	vf	-	-	-	-	-	-

TABLE 3.4, cont'd

* - color from Munsell Color Charts, 1995;
** - done on particles of <2 mm, classes: sil=silt loam; c=clay, cl=clay loam, sic=silty clay, sicl=silty clay loam, l=loam;
# - 1=weak, 2=moderate, 3=strong; f=fine, m=medium, c=coarse; sbk=subangular blocky, pr=prismatic, pl=platy;
‡ - redoximorphic features; 1=few, 2=common, 3=many, f=fine, m=medium, c=coarse, fn=faint, d=distinct, p=prominent, mtl=mottled horizon;
§ - v =very, fr=friable, f=firm;
¶ - 1=few, 2=common, 3=many, vf=very fine, f=fine, m=medium, ch=root channels, krot=krotovinas;
† - a=abrupt, c=clear, g=gradual, s=smooth, w=wavy, d=diffuse;
& - 1=few, 3=many, f=fine, th=threads, pc=pockets, m=masses;
$ - carbonate nodules , 1=few, 2=common, 3=many, f=fine, no=nodules;
£ - 1=few, 2=common, f=fine, c=coarse, sb=soft bodies, con=concretions, no=nodules;
Ω - Cr horizon had pockets of C material with 10YR 6/1 matrix, common coarse prominent 10YR 6/8 mottles, silty clay texture and massive structure;

TABLE 3.5

CHEMICAL AND PHYSICAL PROPERTIES OF THE SAMPLED PROFILES

Horizon	Depth	pH field	pH paste	pH 1:1*	EC#	SAR¶	Organic carbon	Exchangeable acidity	DSP†	Bulk density
	cm				dS m^{-1}		%	$cmol_c/kg$	%	g/cm^3
Type 1 - Natrudalfs										
Wing Soil Series (site 3)										
Ap	20	7.0	6.8	6.8	0.50	5.1	1.4	8.29	nd	1.59
Bt1	41	6.5	6.1	5.6	1.10	23.4	0.8	10.82	52.8	1.92
Bty2	72	7.0	6.7	6.6	4.00	12.2	0.7	8.39	79.3	1.95
2Btk3	115	8.0	7.2	7.5	3.70	30.5	0.2	5.95	85.6	1.77
2BCk	170+	8.0	8.3	8.6	1.90	26.2	0.1	3.51	78.9	1.83
Lafe Soil Series (site 6)										
Ap	12	8.0	7.5	6.4	11.4	25.6	1.3	7.90	nd	1.81
Btn1	30	8.0	7.3	8.0	12.2	27.0	0.5	3.71	19.8	1.92
Bty2	55	8.0	7.6	8.3	10.6	30.6	0.2	1.76	0.0	1.84
Btky3	95	8.0	7.9	8.7	5.20	17.3	0.1	3.32	58.0	1.93
BCk	140	8.0	8.5	8.9	3.20	35.2	0.1	2.63	53.5	1.75
2Cr1	170	8.0	7.7	8.1	1.41	25.3	0.4	2.92	nd	1.72
2Cr2	195+	8.0	8.0	8.5	1.60	18.2	0.5	2.83	nd	1.98
Type 2 – Proposed Sodic Hapludalf										
Dwight Soil Series (site 2)										
Ap	17	6.5	7.4	7.6	0.80	2.3	1.0	6.13	nd	1.66
Bn1	36	6.5	7.7	7.5	0.50	4.9	0.6	6.62	49.3	1.73
Bn2	64	6.5	6.9	6.5	0.70	8.7	0.6	6.49	75.3	1.83
Bt3	110	7.0	7.4	6.4	0.82	11.4	0.7	4.04	87.2	1.82
Bt4	140	8.0	7.6	7.2	0.80	10.8	0.3	4.17	91.3	1.71
BC	170+	8.0	7.3	7.3	0.80	12.1	0.3	4.41	81.7	1.71

TABLE 3.5, cont'd

Horizon	Depth	pH field	pH paste	pH 1:1*	EC#	SAR¶	Organic carbon	Exchangeable acidity	DSP†	Bulk density
	cm				dS m^{-1}		%	cmol$_c$/kg	%	g/cm^3
Type 3 – Proposed Solodic Hapludalf										
Bosville Soil Series (site 1)										
Ap	13	5.5	7.1	5.0	0.37	0.4	1.4	8.09	nd	1.23
E	28	5.5	6.7	5.5	0.24	0.5	0.6	4.86	nd	1.64
Bt1	53	4.5	6.6	5.3	0.12	1.6	0.4	17.94	0.0	1.71
Bt2	76	4.5	6.8	5.7	0.30	5.1	0.3	16.48	27.3	1.80
Bty3	130	4.5	7.0	5.7	0.40	4.6	0.2	10.61	35.0	1.88
Bty4	168	5.5	6.7	5.4	0.60	7.7	0.2	6.88	76.4	1.84
BC	200+	6.5	7.0	5.4	2.40	11.8	0.2	6.88	50.2	1.79
Wister Soil Series (site 4)										
Ap	14	5.5	6.7	6.5	0.40	2.0	1.1	9.07	nd	1.59
E	25	5.5	6.1	6.0	0.15	2.7	0.7	11.99	nd	1.58
Bt1	55	5.5	7.2	6.6	0.35	3.1	1.0	25.35	5.8	1.54
Bt2	78	6.0	6.4	6.2	0.14	4.6	0.7	19.50	11.8	1.76
Bt3	105	6.0	6.9	6.5	0.90	11.7	0.6	14.43	22.2	1.88
Cr	152+	6.0	7.0	6.2	1.70	15.3	0.6	12.29	nd	2.08
Pockets‡		7.0	7.6	nd	1.50	9.0	0.4	nd	nd	nd

- EC=electrical conductivity
¶ - SAR=sodium adsorption ratio
† - DSP=dispersion, Double Hydrometer method data
* - 1:1 soil-water mixture by weight
‡ - pockets of C material in Cr horizon

between sodic soils. Fedorin (1960) noted the presence of a subdivision of Solonetz soils by moisture regime in the Russian classification scheme. Seelig et al. (1990a; 1990b; 1991) and Seelig and Richardson (1994) suggested recognizing moisture conditions in sodic soils evidenced by matrix and redoximorphic features color at a soil subgroup level.

Both profiles showed a rapid increase in clay content between surface and upper subsurface layers (Table 3.4), which is characteristic of sodic soils. The designation "n" in the field was given only for the upper B-horizon of the Lafe soil and was based on sodium salt crust at the area sampled. Both soils have prismatic structure in one horizon in the subsurface, and neither one had siltans (morphologic characteristics of natric horizon, Soil Survey Staff, 1999). In the Wing soil, none of the horizons are designated "n" in the field. Based on a chemical characterization (Table 3.5), all horizons in the Lafe soil and most of the subsurface horizons of the Wing soil are natric.

Mineralogy of the Lafe and Wing soils showed dependence on parent material properties (Table 3.6). In the Lafe soil, an increase in smectite content compared to the Wing soil may be attributed to more extensive presence of the shallow water table ((Allen and Hajek, 1989; Borchardt, 1989). Large amounts of vermiculite and kaolinite in both profiles may be explained by high temperatures and precipitation values inducive of vermiculite and kaolinite formation (Allen and Hajek, 1989; Dixon, 1989; Douglas, 1989).

Based on field description and chemical characterization data, the following sequence of events in the Natrudalfs genesis in humid areas of Oklahoma is suggested: The Wing (site 3) and the Lafe (site 6) soils were developed in alluvium that was rich in sodium salts, and possibly sodium-bearing minerals. Both soils were formed first as saline-sodic

TABLE 3.6

MINERALOGY OF THE SAMPLED PROFILES

Horizon	Depth	Relative abundances#					
		Kaolinite	Illite	Vermiculite	Quartz	Smectite	Mixed
	cm	%					
		Type 1 – Natrudalf					
		Wing Soil Series (site 3)					
Ap	0-20	47	12	35	4	2	-
Bt1	20-41	44	10	43	3	-	-
Bty2	41-72	54	6	33	4	3	-
2Btk3	72-115	16	5	77	1	1	-
2BCk	115-170+	14	8	76	1	1	-
		Lafe Soil Series (site 6)					
Ap	0-12	40	30	18	3	9	-
Btn1	12-30	62	8	16	3	11	-
Bty2	30-55	33	4	60	3	0	-
Btky3	55-95	38	16	30	2	14	-
BCk	95-140	47	13	-	1	-	39¶
2Cr1	140-170	61	26	7	4	2	-
2Cr2	170-195	42	28	22	4	4	-
		Type 2 – Proposed Sodic Hapludalf					
		Dwight Soil Series (site 2)					
Bt3	64-110	10	5	-	3	-	82§

TABLE 3.6, cont'd

Horizon	Depth	Relative abundances#					
		Kaolinite	Illite	Vermiculite	Quartz	Smectite	Mixed
	cm	--% --					
		Type 3 – Proposed Solodic Hapludalf					
		Bosville Soil Series (site 1)					
Bty4	130-168	20	16	-	4	-	60¶
BC	168-200	27	19	-	4	-	50¶
		Wister Soil Series (site 4)					
Ap	0-14	72	13	10	5	-	-
E	14-25	49	9	37	4	1	-
Bt1	25-55	18	6	72	1	-	3
Bt2	55-78	40	9	46	2	3	-
Bt3	78-105	41	9	43	2	4	-
Cr	105-152+	26	60	8	4	2	-
Pockets*		58	16	21	4	1	-

- percentages estimated from areas of diagnostic x-ray peaks
¶ - randomly interstratified illite-smectite mineral
* - pockets of C material in Cr horizon
§ - regularly interstratified illite-smectite mineral

soils. Large amounts of sodium salts were also added due to evaporation from the shallow saline ground water during drought periods. The major anion in the Wing and Lafe soils is a sulfate (Table 3.7) reflecting possible weathering of pyrite, which is common for coal beds (Allen and Hajek, 1989) abundant in McAlester shale underlying alluvium in eastern Oklahoma (Snider, 1917; Moose and Suarle, 1929; Oklahoma Highway Department, 1966; Oklahoma Highway Department, 1970).

As stream course changed, the water table at the Wing soil site may have lowered resulting in better drainage and leaching most of the salts. Relatively impermeable bedrock coupled with high rainfall resulted in a perched water table in winter and spring (Abernathy et al., 1973). Some addition of salts and sodium through upward water movement from the water table continues during hot periods leading to moderate salinity and SAR values. In the Lafe soil, the presence of a relatively impermeable bedrock closer to the surface resulted in poorer drainage (water stands during most of the summer) compared to the Wing soil, and hence salinity and SAR in the profile remained large. The development of saline-sodic soils cannot proceed to sodic in these soils, as it requires leaching, so that is why some researches call saline sodic soils a result of "retarded genesis" (Harper and Plice, 1949).

Considering moisture conditions and resulting salinity, the following division of Natrudalfs into new subgroups is proposed: the Lafe soil series having EC > 8 is put in a *saline* subgroup and the Wing soil with EC < 4 is in a *typic* subgroup.

Type 2 – Proposed Sodic Hapludalf. This type is represented by the Dwight soil (site 2) of the Hapludalf great group based on SAR values (Soil Survey Staff, 1999). The soil has SAR values between 6 and 13 in the first 100 cm of the profile, and SAR almost

Table 3.7

WATER SOLUBLE IONS OF THE SAMPLED PROFILES

Horizon	Depth	Water soluble cations and anions						
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}
	cm	-----	-----	-----	$cmol_c/L$	-----	-----	-----
		Type 1 - Natrudalf						
		Wing Soil Series (site 3)						
Ap	20	0.09	0.03	0.40	0.00	0.11	0.15	0.23
Bt1	41	0.02	0.02	1.07	0.00	0.06	0.92	0.04
Bty2	72	0.92	1.29	4.07	0.01	0.03	5.25	0.07
2Btk3	115	0.1	0.17	3.57	0.00	0.03	4.09	0.13
2BCk	170+	0.04	0.06	1.85	0.00	0.09	1.58	0.46
		Lafe Soil Series (site 6)						
Ap	12	2.44	8.64	19.06	0.04	0.16	15.64	0.32
Btn1	30	2.34	6.85	18.32	0.00	0.08	13.60	0.27
Bty2	55	2.17	4.77	18.01	0.00	0.09	11.30	0.18
Btky3	95	0.41	2.10	6.11	0.01	0.07	7.67	0.30
BCk	140	0.04	0.13	3.26	0.04	0.06	3.87	0.55
2Cr1	170	0.03	0.06	1.51	0.00	0.06	0.96	0.51
2Cr2	195+	0.05	0.10	1.57	0.00	0.07	1.09	0.53
		Type 2 – Proposed Sodic Hapludalf						
		Dwight Soil Series (site 2)						
Ap	17	0.30	0.16	0.36	0.01	0.32	0.10	0.30
Bn1	36	0.11	0.05	0.43	0.00	0.16	0.08	0.27
Bn2	64	0.07	0.02	0.58	0.01	0.11	0.43	0.07
Bt3	110	0.06	0.03	0.76	0.00	0.23	0.41	0.10
Bt4	140	0.05	0.03	0.69	0.00	0.40	0.12	0.22
BC	170+	0.04	0.02	0.68	0.00	0.32	0.12	0.27
		Type 3 – Proposed Solodic Hapludalf						
		Bosville Soil Series (site 1)						
Ap	13	0.18	0.07	0.04	0.03	0.10	0.04	0.17
E	28	0.12	0.05	0.04	0.01	0.04	0.02	0.07
Bt1	53	0.03	0.01	0.07	0.00	0.05	0.03	0.03
Bt2	76	0.03	0.03	0.29	0.02	0.13	0.03	0.13
Bty3	130	0.04	0.03	0.28	0.00	0.23	0.05	0.02
Bty4	168	0.05	0.03	0.51	0.01	0.42	0.07	0.02
BC	200+	0.24	0.31	1.97	0.01	1.53	0.77	0.03
		Wister Soil Series (site 4)						
Ap	14	0.10	0.05	0.18	0.01	0.08	0.04	0.18
E	25	0.03	0.01	0.12	0.00	0.05	0.00	0.00
Bt1	55	0.06	0.04	0.22	0.00	0.09	0.03	0.17
Bt2	78	0.01	0.00	0.12	0.01	0.07	0.04	0.00
Bt3	105	0.05	0.04	0.81	0.01	0.05	0.72	0.00
Cr	152+	0.10	0.13	1.67	0.00	0.10	1.93	0.03
Pcts*		0.22	0.23	1.35	0.00	0.05	1.37	0.10

* - pockets of C material in Cr horizon

reaches value of 13 deeper in the profile. The proposed subgroup for the Dwight soil is *sodic,* reflecting values of SAR reaching values of > than 6 within the upper 40 cm of the argillic horizon. *Sodic* subgroups are used in some great groups in Soil Taxonomy (Soil Survey Staff, 1999) to include soils with SAR values within a range of 6 to 13 within 40 or 100 cm of the mineral soil surface. Soils with SAR values in a range of 6 to 13 are also distinguished into a separate taxonomic category in FAO classification (FAO, 1998) and in Russian classification (Kaurichev, 1989).

Very low EC may account for the highest dispersion values recorded in this study compared to soils of the Bosville, Wing, Wister, and Lafe series. A lower pH than in the Natrudalfs indicates a better leaching environment on a high terrace landscape position. Uniform grayish color throughout the profile may be explained by soil moisture conditions. The Dwight soil is located in a large depression, which in the humid climate of the area may contribute to prolonged wetness of the soil causing reducing conditions. This phenomenon may have caused uniform salinity in the profile.

Presence of a sodic soil on a terrace in a humid climate of Oklahoma is supported by impeded drainage and a shallow water table common in lower positions on a landform. Seelig and Richardson (1994) found sodic soils in North Dakota in upland positions due to moisture trapped in relatively shallow coarse-textured substrata. Due to overall high position on a landscape, sodium and salts were leached out of the profile. This results in low salinity of the profile, which along with relatively high sodium content caused high dispersion in the profile.

Type 3 – Proposed Solodic Hapludalf. The Bosville (site 1) and Wister soils (site 4) represent the third type - leached sodic soils of the Hapludalf great group. The SAR values are between 6 and 13 within 2 m of the soil surface (Table 3.4). The EC is low at the surface and reaches values of more than 2 in the subsoil (BC or Cr horizons in the Bosville and Wister soils respectively). These soils are at the next stage of Solonetz soil evolution, Solods, evidenced by higher exchangeable acidity and lower pH (Table 3.4) as well as low EC and SAR values. Solods with high sodium and soluble salts deep in the profile, acidic reaction, and eluviation horizon are described as a separate taxonomic category in Russian (Kaurichev, 1989) and Canadian (Agriculture Canada Expert Committee on Soil Survey, 1987) soil classification schemes. The proposed subgroup name for the soils of the third type is *solodic Hapludalfs*.

The Bosville soil is characterized by high dispersion values in the bottom of the agrillic and in BC horizons, while in the Wister soil the same values of SAR did not result in dispersion (Table 3.3). Insensitivity of the Wister soil a large sodium content may be explained by high acidity and high amounts of kaolinite in the clay fraction of the profile. Acidic kaolinitic soils have been considered insensitive to changes in sodium content on the exchange complex (Levy, 2000). Solodic Hapludalfs should be further differentiated based on physical properties, i.e. dispersion. Wister should be recognized as *non-dispersive* and Bosville as *dispersive* solodic Hapludalfs.

Morphology of these two soils reflects a highly leaching environment and better drainage conditions compared to the soils of the first and the second types. The Wister soil, due to closeness to a relatively impermeable shale, has more reducing conditions evidenced by abundant redoxomorphic features (Table 3.4).

Clay mineralogy of the Bosville and Wister soils reflects parent material properties as well as climate effect. Both soils were formed from micaceous parent material

(Knechtel, 1949). In the Wister soil, large amounts of kaolinite and vermiculite were formed due to acid weathering in a humid environment (Allen and Hajek, 1989; Dixon, 1989; Douglas, 1989).

The Bosville and Wister are leached soils. The Bosville soil was developed in alluvium with a high content of sodium salts. The Wister soil was developed in McAlester shale. Geologic records do not identify extensive salt deposits in a bedrock of the eastern Oklahoma (Knechtel, 1949; Oakes, 1952; Davis, 1960; Oakes, 1963; Johnson, 1979), though the ground water of the area is characterized by the presence of pockets of a highly mineralized water (Warren, 1952; Davis, 1960; Motts, 1963). In the past, under more humid climate (Alberts, 1981; Ferring, 1995), water table, rich in sodium salts was closer to the surface and coupled with high temperatures in summer, resulted in accumulation of sodium salts in the soils. With the climate becoming more arid (Ferring, 1995), a water table lowered leading to the leaching of the salts. Annual fluctuations of water table level resulted in the accumulation of sodium on the exchange complex. In the Bosville soil, high sodium content on the exchange complex led to the formation of prismatic structure. High contents of sodium also caused dispersion followed by leaching clays from the surface horizons and the formation of siltans in macropores. In the Wister soil, dispersion of clays did not take place, possibly due to a higher acidity and higher content of kaolinite (clay mineral, which is insensitive to sodium concentrations, Levy, 2000) compared to the Bosville soil. This resulted in the formation of a blocky structure and lack of siltans. With time, the leaching process resulted in moving salts and sodium down the profile of both soils. Sodium on the exchange complex was replaced with hydrogen. At that time, the soils were covered with forest (Albert, 1981) and developed an E-horizon. Prismatic structure at the top of the natric horizon in the Bosville soil has disintegrated into a blocky structure. Such soils with Solonetz structure and low sodium content are common in the U.S. (Soil Survey Staff, 1999).

Three types of sodic soils represent three stages in sodic soil formation as it is pictured by a classic theory (Sigmond, 1926; Gedroitz, 1927; Nikiforoff, 1930; Kellog, 1934).

Distribution of Sodic Soils

Based on the information obtained from the field and laboratory data and from the literature (Oklahoma Highway Department, 1966; Oklahoma Highway Department, 1970; Abernathy, 1970; Shingleton, 1971; Abernathy et al., 1983), a hypothetic distribution of three types of sodic soils on landscapes of the eastern Oklahoma was suggested (Fig. 3.2). The first type, Natrudalfs (the Wing and Lafe soils) occurs on old terrace deposits along small drainageways, mostly intermittent (Abernathy, 1970; Abernathy et al., 1983). In this landscape position a shallow water table exists over a long period of time allowing *saline* sodic and *typic* sodic soils (soils with high sodium) to persist even in a humid climate (under high precipitation). The second type, sodic Hapludalf (the Dwight soil), occurs on high terrace deposits (intermediate position) where precipitation leached salts and sodium from the upper soil horizons. The third type, solodic Hapludalfs (the Bosville and Wister soils), may form on high terrace

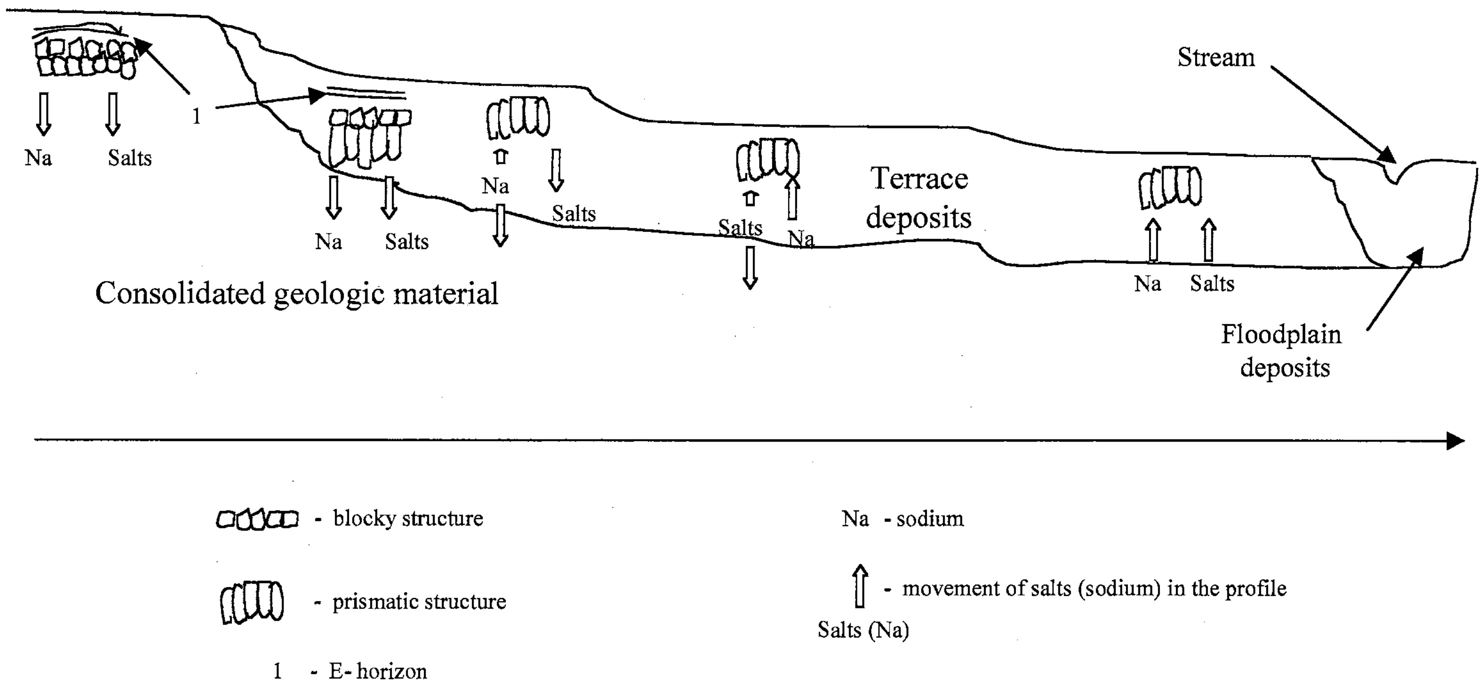

Fig. 3.2. Hypothetic Distribution of Sodic Soils on Landscapes of Eastern Oklahoma

deposits or in residuum on uplands under native forest cover. These soils are exposed to a pronounced leaching and develop eluvial horizons, low pH, and high exchangeable acidity with sodium and salts in BC or C-horizons. The presence of sodic soils of two types (two subgroups) in the intermediate position was recorded by Seelig et al. (1990a) on the landscapes of South Dakota.

Sodic soils of the Wing and Lafe series cover a small area compared to the leached soils of the Wister and Bosville series. The Wing and Lafe soil were more widespread in southeast Oklahoma in the past and have changed into non-sodic soils due to high precipitation values in the region compared to sodic soils in western drier (mean annual precipitation of 61-91 cm) part of the state. Soil as Bosville may be found on the same landscapes as the Dwight, Wing, Wister, and Lafe soils.

Conclusions

The difference in leaching conditions of Bosville, Dwight, Wing, Wister, and Lafe soil series accounts for their different morphology, absolute amount of sodium, values of SAR, salinity, soil reaction (pH), exchangeable acidity and mineralogy and distribution of these parameters along the soil profile.

Three types of sodic soils form under the humid conditions of southeast Oklahoma. The first type, Natrudalfs, has SAR up to 30 and moderate to high salinity (EC > 2) compared to soils of other types. Natrudalfs occur in the lowest position on the landscape and have impeded drainage evidenced by redoximorphic features. Natrudalfs have a shallow water table for most of the year and are often saline and may not be dispersive (the Lafe soil). Soils with better drainage conditions (the Wing soil) are dispersive throughout the profile. Natrudalfs are recognized as sodic at a high taxonomic level such as great group (Soil Survey Staff, 1999). The second type of sodic soils in the humid region of Oklahoma, sodic Hapludalfs, is located on an intermediate landscape position and formed in alluvium. Characterized by better drainage compared to Natrudalfs, sodic Hapludalfs have low salinity, but soluble sodium is still relatively high to render these soils dispersive. The third type in the sodic soil-landscape sequence is the leached sodic soils of terraces and uplands, solodic Hapludalfs. These soils have a large sodium and salt content at the bottom of the solum compared to Natrustalfs and sodic Hapludalfs. High acidity and kaolinitic mineralogy may result in insensitivity of some of the solodic Hapludalfs (the Wister soil) to sodium content compared to Natrustalfs and sodic Hapludalfs, and the subgroup name suggested for those is *solodic nondispersive.* Less acidity and small amounts of kaolinite in other soils of the solodic Hapludalfs (the Bosville soil) results in high dispersion and is conveyed by another subgroup name, *solodic dispersive.*

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APPENDIX

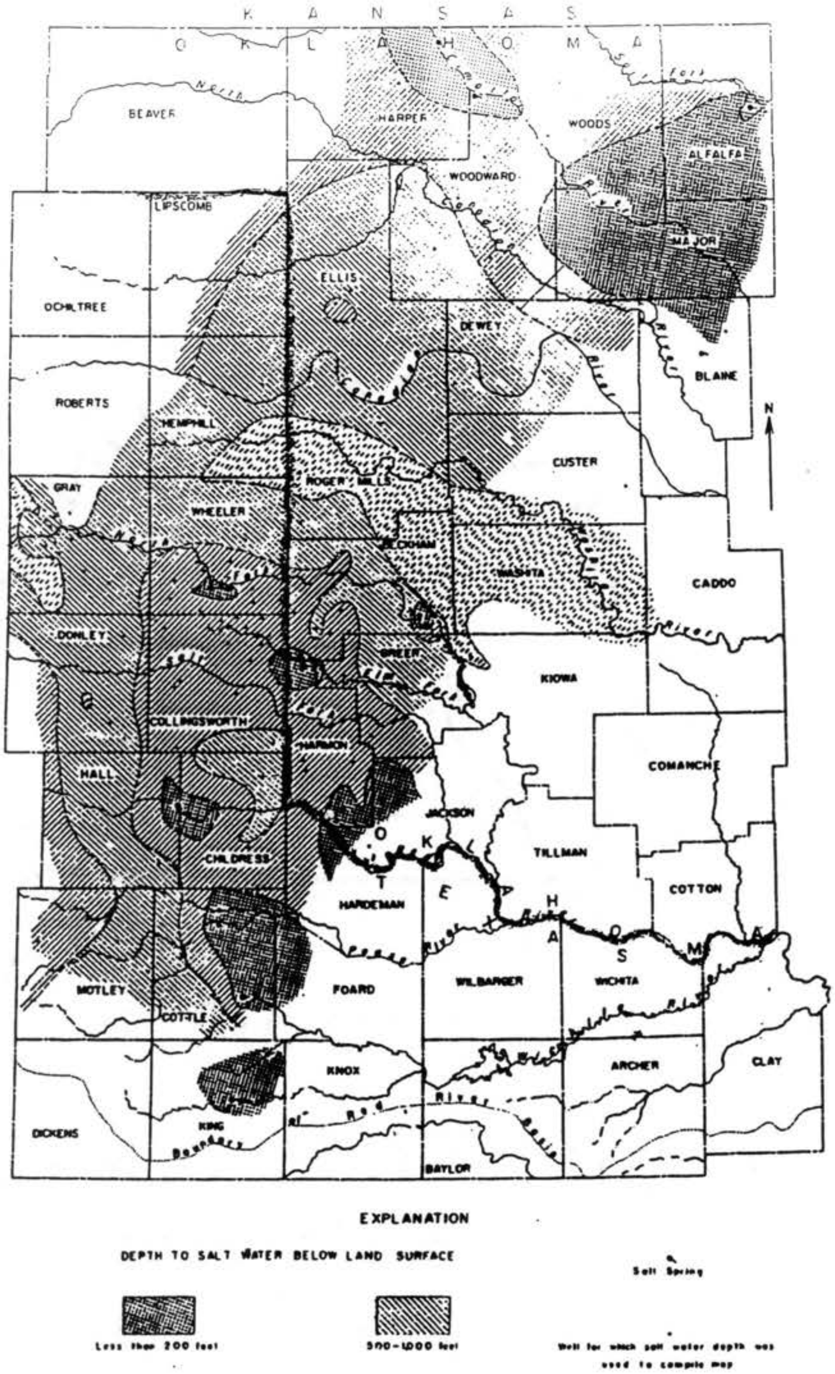

Fig. 1. Map of Western Oklahoma and Adjacent Parts of Texas Showing the General Depth to Salt Water. From Ward (1961).

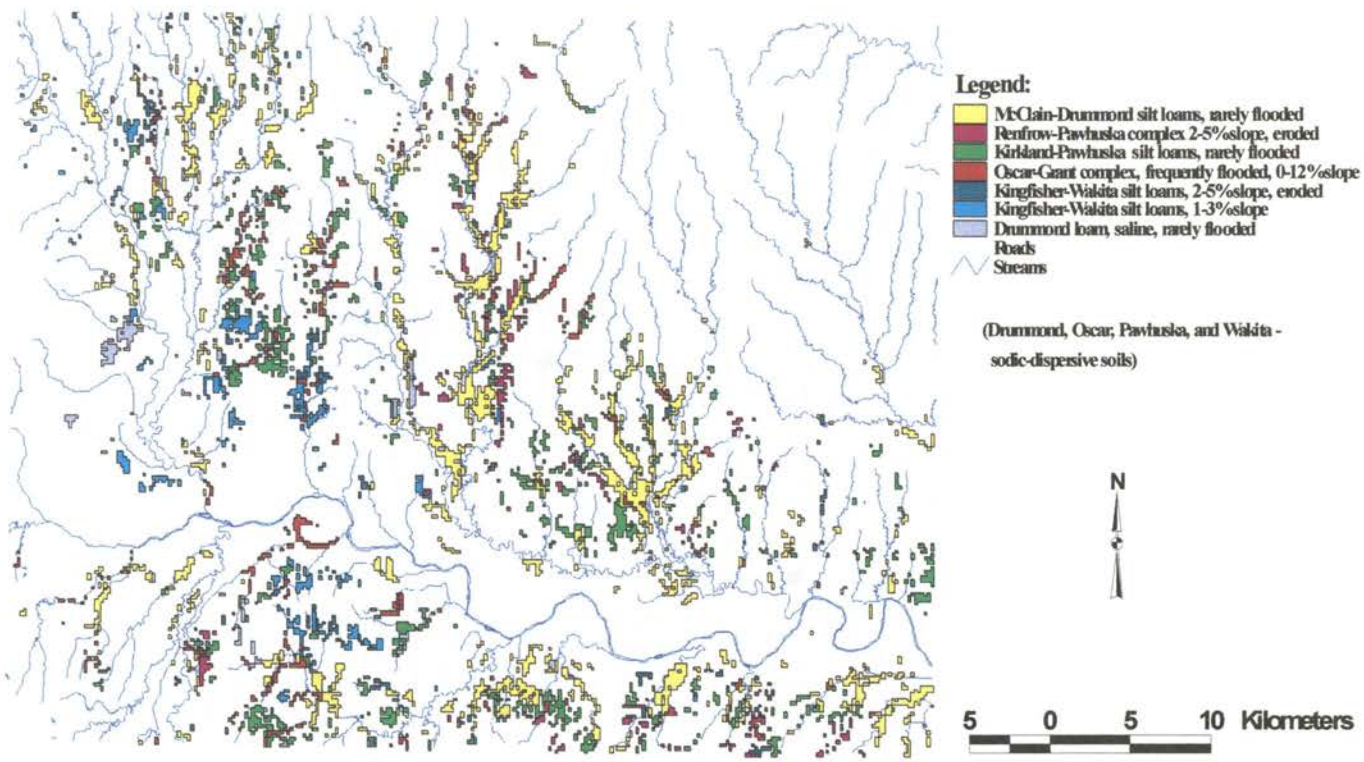

Fig. 2. Modern Distribution of Sodic Soils in Grant Clounty.
From: Williams et al. (1985)
Map compiled by Elena Jigoulina

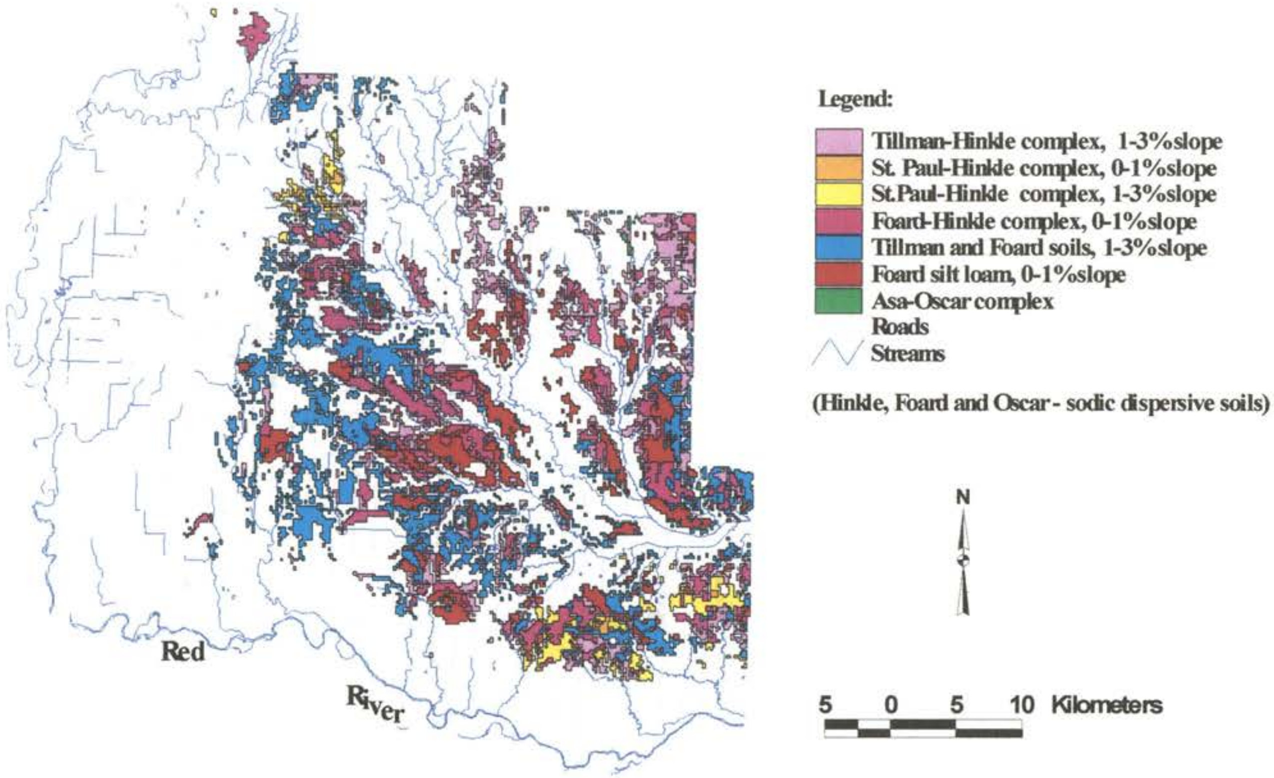

Fig. 3. Modern Distribution of Sodic Soils in Tillman County, Oklahoma.
From: Lamar and Rhodes (1974)
Map compiled by Elena Jigoulina

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