POLISH JOURNAL OF SOIL SCIENCE
VOL. XXXIX/2 2006 PL ISSN 0079-2985

Soil Genesis

CEZARY KABAŁA*

DIAGNOSTIC *SPODIC* HORIZONS IN PODZOLS OF THE SUDETY MOUNTAINS

Received April 28, 2006

Abstract. Bh horizons of Podzols formed from regoliths of sandstones, granites and gneisses in the Sudety Mountains are dark in colour, rich in organic substance, strongly acidic and slightly saturated with basic cations. They are also significantly enriched with organic and amorphous compounds of iron and aluminium. They meet all the morphological and physicochemical requirements of illuvial *spodic* horizons. Despite the evidence of lithological stratification of slope covers and possible polygenesis of B horizons, it is justifiable to classify these soils as Podzols, as adequately describing their morphology, basic properties and tendencies for present development.

The soil cover of the Sudety Mountains is abundant in Cambisols [1], but favourable geological, climatic and biotic conditions facilitate the development of the podzolization processes [18]. Podzols have been identified, with regard to their morphological features and physicochemical properties, in almost every range of the Sudety Mountains [6, 10]. However, the genesis of Podzols in mountainous regions is controversial, due to lithological stratification of slope covers, and especially due to the occurrence of the upper slope cover (theta), which according to Kowalkowski [9] possesses the features of a master E horizon throughout the entire thickness. High concentrations of free iron and aluminium in regoliths of igneous and metamorphic rocks may result in saturation and immobilization of metalo-organic complexes, preventing podzolization of soils constituted from these regoliths [13]. The light colour of the surface soil horizons in the mountains, identified as the effect of podzolization, is sometimes reported to be an effect of water stagnation and periodic occurrence of reducing conditions [2].

In the majority of contemporary soil classification systems, the identification of Podzols is associated with the presence of an illuvial *spodic* diagnostic horizon, although the qualitative and quantitative criteria for its definition show many

*Asst. Prof. C. Kabała, DSc.; University of Agriculture, Institute of Soil Science and Agricultural Environment Protection, Grunwaldzka 53, 50-357 Wrocław, Poland.

discrepancies [3, 8, 14]. The discussion on genesis and classification of mountain soils showing the morphology of Podzols should therefore be focused on the properties of sub-surface horizon enrichment, identified as Bh and Bs.

The purpose of the present investigation was to analyse some morphological features and physicochemical properties of illuvial horizons of Podzols developed from regoliths of selected sedimentary, igneous and metamorphic rocks of the Sudety Mountains, with respect to the definition of the *spodic* diagnostic horizon, and to discuss the simple or polygenetic origin of these soil profiles.

METHODS

The paper presents the results of the analysis of 15 profiles of forest Podzols developed from regoliths of quartzitic sandstone (Stołowe Mountains), granite (Karkonosze and Rudawy Janowickie Mountains) and gneiss (Izerskie Mountains, Śnieżnik Massif and Sowie Mountains). The parent rocks of the soils under investigation were slope materials, usually stratified, but without additions of moraine, alluvial or eolian materials. All the soil pits were located in spruce stands (under mountain dwarf pine stand only in the Karkonosze), on slopes with varying inclinations and relief, at altitudes from 685 to 1330 m a.s.l. Annual mean temperatures in the Sudety Mountains range from 2°C (the Karkonosze Mountains) to 6°C (the Sowie Mountains), and annual mean precipitation is found within the range of 700 to 1300 mm. The annual climatic water balance (the difference between precipitation and evaporation) is positive in the entire region and ranges from +100 to above +600 mm year^{-1}.

The morphological features of the soil horizons (thickness, colour, structure, accumulation of organic matter etc.) were described in the field by standard methods [4]. Bulk samples were air-dried, homogenized, and sieved (<2 mm) in the laboratory, to separate rock fragments (soil skeleton). Particle-size analysis was determined by sieve and areometer methods, following pre-treatments to remove organic matter, and chemical dispersion with sodium hexametaphosphorate. Organic carbon was determined by acid-dichromate hot digestion with $FeSO_4$ titration. Soil pH was determined in a 1:2.5 soil:water suspension. Exchangeable basic cations were measured with 1 mol kg^{-1} ammonium acetate saturation buffered at pH=7. Exchangeable acidity and aluminium were extracted by 1 mol kg^{-1} KCl with 0.01 mol kg^{-1} NaOH titration.

The analysis of mineral samples included the determination of:

– total iron (Fe_t) and aluminium (Al_t) – consumed with a mixture of concentrated $HF + HNO_3$,
– amorphous iron (Fe_{ox}) and aluminium (Al_{ox}) – extracted with ammonium oxalate at pH=3,

– organically complexed iron (Fe_p) and aluminium (Al_p) – extracted with 0.1 mol kg^{-1} sodium pyrophosphate (all three above methods described by Loeppert and Inskeep [11]).

Due to space limitations, the present paper only summarizes the properties of the B horizons and does not contain full description of soil profiles or complete results of laboratory analyses.

RESULTS AND DISCUSSION

Although the presence of the eluvial horizon is not required for identification of Podzols in the majority of soil classification systems, all the profiles under investigation have eluvial E horizons of at least 4 cm thick, identified with regard to the light colour and lower concentrations of organic matter, iron and aluminium. The upper boundaries (transitions) of the B horizons were clear, sometimes even abrupt. The B horizons in all the profiles were divided into clearly distinctive Bh and Bs subhorizons (subhorizon symbols have been simplified since a number of B horizons shows evidence of both non-illuvial and illuvial genesis, given a variety of symbol combinations in the descriptions of soil profiles). The thickness of Bh subhorizons averaged 9 cm (sandstone), 7 cm (granite), and 11 cm (gneiss), and the thickness of Bs horizons was at least twice higher and averaged 21, 14 and 20 cm, respectively. The upper limit of the B horizons was found at depths of 11–16 cm (depending on parent rock type). This shows that both the thickness and the depth of the upper limit of the Bh horizons fulfilled the basic criteria of the *spodic* horizon [3, 8, 14]. The depth of the upper limit of the *spodic* horizon is not defined in the Polish soil classification systems.

The Bh horizons of all the soil profiles under investigation are dark brown, and those in the subalpine zone of the Karkonosze Mountains are almost black (hue mostly 7.5YR on the Munsell scale, value 2-4, chroma 2-4). The Bs horizons are generally much lighter, but their chroma is browner or more rusty (Table 1). As regards Bh subhorizons, all of them fulfil the colour requirements of the *spodic* horizon [3, 8], whereas the chroma of the majority of Bs subhorizons is very intense. These findings may confirm the non-illuvial genesis of some Bs subhorizons [5].

TABLE 1. THE COLOUR VARIABILITY OF THE Bh AND Bs SUBHORIZONS OF PODZOLS DEVELOPED FROM VARIOUS PARENT MATERIALS IN THE SUDETY MOUNTAINS

Soils developed from regoliths of	Soil subhorizon	
	Bh	Bs
Sandstones	7.5YR 4/2-3	7.5YR 5/4-8
Granites	7.5YR 2-3/2	7.5YR 3/4-6
Gneisses	7.5YR 3/2-4	7.5YR 4-5/5-6

The B horizons were low (2-8%) in the clay fraction (the lowest rate was found in soils formed from granite regoliths), whereas the percentage of silt fraction (0.05-0.002 mm) was within a wider range, i.e. from 14 to 50%. The most common texture group of these horizons is sandy loam, while less common is loamy sand or sandy silt. A very common feature of the studied soils is the diversified texture in fine earth or skeletal fractions, which must have influenced the formation of the soil profiles, particularly the E and B horizons. In the field the observed water permeability of some B horizons was lower than that expected with respect to texture, due to the presence of cemented iron pans (especially in Bh horizons) or a massive structure (fragipan-like).

The reaction of B horizons from all the soils under examination was strongly acidic (pH_{H_2O} 3.8-4.1) and no significant differences between Bh and Bs subhorizons were found (Table 2). The B horizons were relatively high in organic carbon and the difference in carbon content between B and overlying E horizons was at least twofold, while the difference in soils constituted from sandstone regoliths was even tenfold. The mean concentration of organic carbon was particularly high in the Bh horizons (from 2.5 to 6.1%), while it was found within the range from 1.4 to 2.7% in the Bs subhorizons. The highest content of organic carbon was found in soils constituted from granite in the subalpine zone of the Karkonosze Mountains (Table 2). The B horizons exhibited very low base saturation (below 15%), always higher in the Bs than in the Bh subhorizons, particularly in soils developed from sandstone regoliths (Table 2).

TABLE 2. SELECTED PHYSICO-CHEMICAL PROPERTIES OF THE Bh AND Bs SUBHORIZONS OF PODZOLS IN THE SUDETY MOUNTAINS (MEAN VALUES)

Soils developed from regoliths of	TOC (%)		pH_{H_2O}		Base saturation (%)	
	Bh	Bs	Bh	Bs	Bh	Bs
Sandstones	2.46	1.38	3.9	4.0	7.5	14.8
Granites	6.10	3.01	3.9	4.0	5.1	6.3
Gneisses	3.75	2.65	3.8	4.1	11.5	13.3

Concluding then, the Bh and Bs subhorizons of Podzols are rich in organic carbon, are strongly acidic and have low saturation with exchangeable base cations, and therefore they fulfil the basic physicochemical criteria of the *spodic* horizon – pH_{H_2O} ≤5.9, organic carbon content ≤ 0.6% [3, 8] and base saturation below 20% [17].

Podzolization is strictly connected with aluminium and iron translocation from surface (eluvial) to subsurface (illuvial) horizons. A diagnostic feature of an illuvial *spodic* horizon is, therefore, the quantitative accumulation of active iron and aluminium. In the present study, we analysed the concentrations of pyrophosphate-extracted iron and aluminium, i.e. the organically complexed as well as oxalate extracted, that is the amorphous, non-crystalline forms of these elements [11]. The highest concentrations of the two forms of iron and aluminium were found in the B horizons in all the soil profiles (Fig. 1). The concentrations of amorphous iron in the Bh horizons of soils developed from granite and gneiss regoliths were 18-27-fold higher, while those formed from sandstone regoliths even 150-fold higher than those found in the E horizons. Such great differences in the concentration of iron and aluminium along with organic substance accumulation in the B horizons are typical of the podzolization processes [12]. Maximum accumulation of amorphous iron (0.58-1.21%) and aluminium (0.35-1.52%) is usually found in the Bh subhorizons. The highest accumulation in the Bs horizons was found only in soils formed from granite regoliths (Fig. 1).

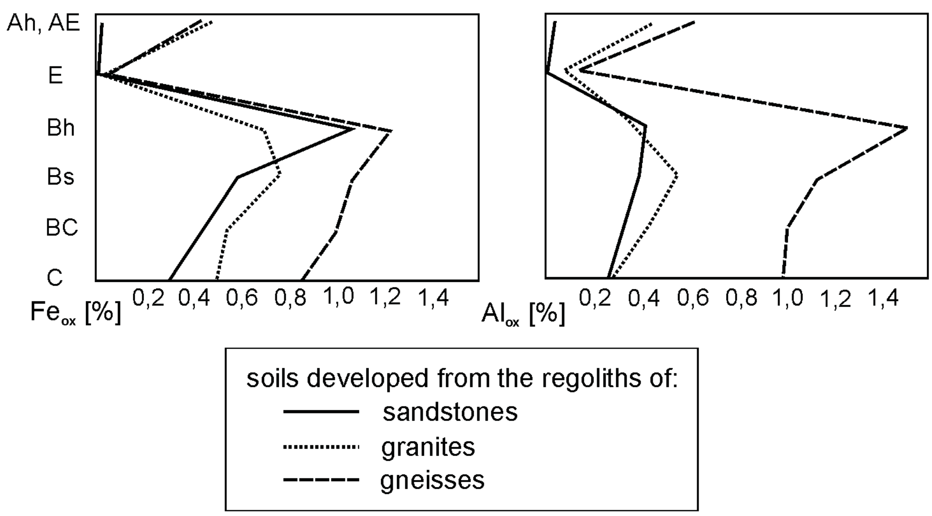

Fig. 1. Vertical distribution of amorphous forms of iron (Fe_{ox}) and aluminium (Al_{ox}) in Podzols of the Sudety Mountains (mean values).

High concentrations of active iron and aluminium in the B horizons are not sufficient evidence of their illuvial genesis, since high concentrations of free iron and aluminium can be found in some horizons developed from *in situ* weathered regoliths [12]. However, the total iron and/or aluminium concentrations in the profiles under investigation were significantly higher in the B horizons comparing to the parent rock (Fig. 2), which must have been a result of illuvial enrichment of the B horizons.

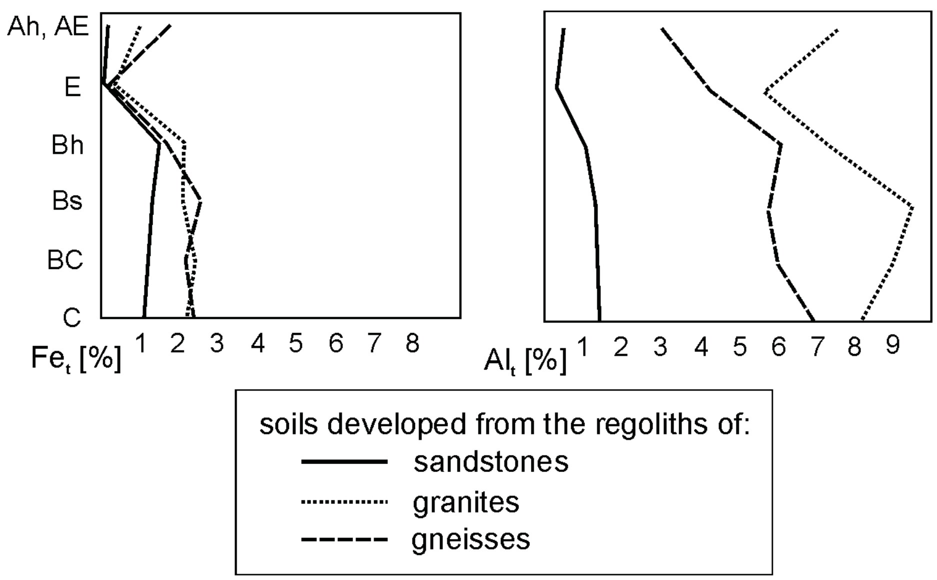

Fig. 2. Total iron (Fe_t) and aluminium (Al_t) concentration in Podzol profiles of the Sudety Mountains (mean values).

The definition of *spodic* horizon is based on the classification of Polish soils [17] using the Mokma illuviation index, i.e. the ratio of carbon to the sum of iron and aluminium in pyrophosphate extracts. Mean values of the ratio C_p/Al_p+Fe_p in the Bh horizons of the analysed soils ranged from 1.5 to 4.1 (in relation to parent material), while the values required should be within the range of 5.8 to 25 [17]. It can, therefore, be concluded that the B horizons of the studied soils cannot be considered *spodic*, as none of the soils can be included in a Podzol typological unit. Similar conclusions were earlier reported by Karczewska *et al*. [7]. In the recent classification systems [3, 8], *spodic* is identified with regard to an amorphous aluminium and iron concentration index (Al_{ox}+1/2Fe_{ox}). Their mean values found in the Bh horizons were within the range 0.64% (soils formed from granite regoliths) to 1.54% (soils formed from gneiss), with a minimum required level of 0.5%. Besides this, FAO (1998) classification requires the value of this index to be at least twice higher in the *spodic* than in overlying E or A horizons. The concentration index in the B horizons of the analysed soils was 7-fold higher in soils developed from granite and gneiss regoliths, and almost 50-fold higher in soils from sandstone regoliths.

Podzols are frequently reported from the mountain belts with various climate conditions in the North and Central Europe. The podzolization process is presently identified in these soils on the basis of the quantitative translocation of amorphous aluminium and iron. Sommer *et al*. [14] found up to 0.95% Feox and 2.45% Al_{ox} in the spodic horizons of Podzols developed from the granite regoliths in the Black Forest Mountains. High concentrations of iron and aluminium resulted in elevated values of the concentration index (Al_{ox}+1/2 Fe_{ox}), between 1.5 and 2.8%, significantly higher than in soils developed from granite in the Karkonosze Mountains, but similar to the values found in soils developed from gneiss regoliths in the Izerskie Mountains and the Śnieżnik Massif (Table 3). In spodic horizons of typical Podzols developed from the sandstone regoliths in the Black Forest, Sommer *et al*. [15] reported up to 0.60% Fe_{ox} and 0.55% Al_{ox}, and a concentration index (Al_{ox}+1/2 Fe_{ox}) between 0.6 and 0.8%. The given values are lower than those found in the spodic horizons of Podzols developed from sandstone in the Stołowe Mountains. The concentration index in the B horizons, as well as the difference among index values in the B and E layers, fulfil the requirements of spodic horizon for FAO-WRB classification [3] in all the soils described above. The thickness and other properties (colour, organic matter concentration, pH values) of the B layers (and sublayers) in Podzols of the Black Forest and the Sudety Mountains are similar and fulfil the requirements of the spodic diagnostic horizon as well. Sommer *et al*. [14, 15] emphasized, however, that significant variability of thickness and other properties of spodic horizons are dependent on the pedon location on the slope and the impact of the lateral podzolization process.

TABLE 3. MEAN VALUES OF ILLUVIATION IN E AND Bh HORIZONS OF PODZOLS OF THE SUDETY MOUNTAINS

Soils developed from regoliths of	$C_p/(Fe_p+Al_p)$[1]		Al_{ox} + 1/2Fe_{ox}, %[2]	
	E	Bh	E	BH
Sandstones	4.6	1.5	0.02	0.94
Granites	5.4	4.1	0.09	0.64
Gneisses	3.1	1.6	0.19	1.54

[1]carbon, iron and aluminium in a pyrophosphate extract; [2]aluminium and iron in an oxalate extract.

Chemical properties of the illuvial horizons in thin Podzols of the Karkonosze Mountains (in a subalpian zone) are similar to these reported by Stuetzer [16] in the alpine belt of the Rondane Mountains, South Norway. However indexes of amorphous iron and aluminium concentration (Al_{ox}+1/2Fe_{ox}) do not meet the requirements of spodic horizon in all profiles, but the translocation of amorphous iron and, particularly aluminium from the E to B horizons, is easily visible in all studied soils. Stuetzer concluded [16] podzolization to be an active process in alpine environments, and the accumulation of amorphous iron and aluminium to be a good indicator of initial Podzol formation.

CONCLUSIONS

1. The Bh horizons of Podzols that developed from regoliths of sandstones, granites and gneisses in the Sudety Mountains fulfil the morphological and physicochemical requirements of illuvial *spodic* horizons. The properties found in the Bh horizons, although related to the kind of parent material, account for the advanced podzolization processes.

2. Despite the lithological stratification of slope covers and possible polygenetic origin of some B horizons, it is justifiable to classify these soils as Podzols due to the morphology of soil profile, physico-chemical properties of soils, and dominant tendencies of their present development.

3. The index of amorphous iron and aluminium concentration (Al_{ox}+1/2Fe_{ox}) used in the international soil classification system is suitable for identification of *spodic* horizons in mountain soils. The values of the Mokma illuviation index were significantly lower than required by the previous official version of Polish soil classification.

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WŁAŚCIWOŚCI POZIOMU DIAGNOSTYCZNEGO *SPODIC* W GLEBACH BIELICOWYCH SUDETÓW

Poziomy Bh gleb bielicowych wytworzonych ze zwietrzelin piaskowców, granitów i gnejsów na obszarze Sudetów są ciemno zabarwione, zasobne w substancję organiczną, silnie kwaśne i bardzo słabo wysycone kationami zasadowymi, wyraźnie natomiast wzbogacone w organiczne oraz amorficzne połączenia żelaza i glinu. Spełniają wszystkie kryteria morfologiczne oraz fizykochemiczne dla poziomów iluwialnych *spodic*. Mimo morfologicznych i litologicznych przejawów poligenezy poziomów B badanych gleb, uzasadnione jest zaliczanie tych gleb do typu bielicowego, co właściwie charakteryzuje ich budowę morfologiczną i podstawowe właściwości, oraz dominujący, aktualny kierunek rozwoju tych gleb.