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PODZOLIZATION – AN ADDITIONAL PARADIGM

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Abstract. Present models of podsolization emphasize the mobilization and precipitation of dissolved organic matter, together with Al(-silicates) and Fe. Such models cannot explain the dominance of pellet-like organic matter in most zonal podzols, and the discrepancy between the chemistry of percolating organic matter (DOC) and the organic matter accumulated in podzol-B horizons.

The present paper offers an explanation in which dynamics of the rooting system of the vegetation, and the decay of its litter is combined with leaching by organic acids. Such a model can explain the dominance of root-derived organic matter podzol-B horizons. It is suggested that organic matter derived from roots is dominant in zonal podzols while illuvial organic matter may dominate in (nutrient-poor of hydromorphic) intrazonal podzols.

INTRODUCTION-CONFILCTS BETWEEN MODEL AND OBSERVATION

Current theories about the podzolisation process, i.e the mobilization of humus and sesquioxide in the topsoil of acidic soils, and their precipitation in a B horizon, are built up of three non-exclusive processes (e.g Browne, 1995; Courchesne & Hendershot, 1997):

- mobilization of unsaturated metal-organic complexes in the forest floor and the A horizon, followed by precipitation upon saturation of organic molecules through metal complexation: the *fulvate theory* (e.g McKeague *et al.*, 1978); with a variant by Browne (1997).
- Transport of sols of (proto-)imogolite allophane, precipitation of these sols in the B horizon and subsequent adsorption of mobile humus: the *proto-imogolite theory* (e.g., Anderson *et al.*, 1982).
- Two stages of profile development which occur sequentially or simultaneously: a) *in situ* formation of imogolite/allophane in the Bs horizon by a carbonic acid weathering process, and b) precipitation of fulvic acid on the Al-rich precipitates in the Bs horizon. This is known as *fulvate-bicarbonate theory* (Ugolini and Dahlgren, 1987).

A variation upon the first model suggests that transport of metals is effected by complexation to low-molecular weight organic acids. Upon breakdown of these carriers, the metals would be transferred to larger organic molecules, and thus cause their precipitation (Van Breemen and Buurman, 2002).

Recent research on Swedish podzols clearly indicated that high-molecular weight OM may precipitate on allophanic material, while LMW-OM plays a significant role in movement of sesquioxides (Riise *et al.*, 2000; Van Hees *et al.*, 2000). Farmer and Lumsdon

(2001) proved that fulvates can be precipitated by proto-imogolite in the laboratory.

In all these theories, the mobilization – transport – precipitation model dominates.

Although partial proof of all the above processes appears to exist, they do not explain all variations in podzol chemistry and morphology. Some of the remaining problems are clear from the various parts of the definition of the spodic horizon in FAO, USDA, and WRB publications. Table 1 gives a compilation of the criteria used in these three systems.

TABLE 1. Criteria for the spodic horizon

Criterion	SSS, 1992 (USDA) "spodic materials"	FAO-Unesco, 1990 "spodic B-horizon"	WRB, 1998 "spodic horizon"
Colour	7.5YR, 5YR or redder or 10YR, dark		7.5YR or redder; or 10YR, dark
Cementation	Yes	Yes	Yes
Organic pellets		Yes	Yes
Cracked coatings	Yes		
Org C content	>0.6		>0.6%
pH-water	<5.9		<5.9
Al_o+0.5Fe_o	>0.5		>0.5
ODOE	>0.25		>0.25
Additional	Movement of OM	$(Fe+Al)_p/(Fe+Al)_d>0.5$; $(Fe+Al)_p/clay>0.2$ d*(CEC8.2-0.5*clay)>65	

These criteria address the quality and accumulation of organic matter and sesquioxides. Two criteria of Table 1 indicate that horizons with essentially different properties are grouped together. First, the organic matter can occur either as cracked coatings (and eventually strongly cement a horizon), or as silt- and sand-size pellets. Second, the colour can either reddish, or black, while transitions do not seem to exist. From the literature it is clear that zonal podzols tend to have strongly coloured B-horizons, with a dominance of iron in the B-horizons, while intrazonal podzols have very dark B-horizons, in which organic matter plays a dominant role. The question arises whether the same process can lead to such different morphological characteristics. Macro- and micromorphology suggest that the phenomena are separate in space:

Macromorphological characteristics

Zonal podzols appear to have more accumulation of sesquioxides, and less of organic matter in the B-horizon than intrazonal podzols (on poor parent materials). As a consequence, zonal podzols have more intense colours. Statistical analysis of podzols in the US indicates dominant B-horizon colours of 7.5YR 4/4 and redder (Base and Brasher, 1990). Such colours are also found in other zonal podzols, e.g. by Monaci *et al.* (1990) in the Italian Alps. By contrast, intrazonal podzols from Western Europe have dominant dark grey or black colours in the top of horizon (e.g. Righi and DeConinck, 1974; Mokma and Buurman, 1980). The darker colours coincide with higher C contents.

Hydromorphic sandy podzols that are devoid of iron frequently have black upper B-horizons (the periodically aerated part) over dark brown unaerated lower B-horizons (Mokma and Buurman, 1980).

Micromorphological characteristics

In micromorphology, two main humus types are distinguished in podzols: polymorphic organic matter (pellets), and monomorphic organic matter (coatings, organans). Organic matter in well-drained zonal podzols is generally polymorphic. The same is found in the B-horizons of well-drained intrazonal podzols (DeConinck *et al.*, 1974; DeConinck, 1980). Actually, many podzol-B horizons contain polymorphic rather than monomorphic organic matter. Polymorphic organic matter can frequently be linked directly to decaying roots. In hydromorphic podzols, monomorphic coatings tend to dominate, especially in cemented horizons (e.g., Thompson *et al.*, 1996).

Micromorphological evidence indicates that pellets may transform into monomorphic-like coatings through a process of "welding", but the transformation of monomorphic coatings to pellets has not been described so far. This indicates that organic matter pellets are formed by decay of plant litter in the soil, but not by biogenic reworking of monomorphic coatings. Therefore, the presence of pellets as the dominant form of organic matter in the podzol-B horizon does not conform to the current transport theories of podsolization.

Chemical characteristics

Very few authors have combined studies on morphology and chemistry of podzol-B humus. Our own studies show that monomorphic organic matter in hydromorphic and well-drained podzols is chemically very different from polymorphic OM in the same soils (Buurman *et al.*, 2002). Nierop (1998), and Nierop and Buurman (1998, 1999) found that in incipient podzols, the organic matter in the B-horizon is predominantly derived from roots and bears no chemical resemblance to dissolved organic matter in the same profiles. Buurman *et al.* (2002) found that polymorphic organic matter chemically resembles roots, while monomorphic OM resembles DOC.

These properties cannot be accounted for by the transport and accumulation model of podzolisation. It appears that the influence of root growth and decomposition has been largely neglected.

Organic matter dynamics

The difference between zonal and intrazonal podzols is also found in carbon dynamics. Organic matter in B-horizons of zonal podzols has a much faster turnover than that in intrazonal podzols. Mean residence times of B-horizon humus are relatively short on rich parent materials (400-500 years; Guillet, 1987; Tam and Holmen, 1967); and much longer in intrazonal podzols on poor sands (2000-3000 years; DeConinck, 1980; Buurman, unpublished data). At equal organic matter inputs, longer mean residence times imply a stronger accumulation of organic matter. Similarly, very short mean residence times, as can be expected in soils rich in nutrients, will lead to low accumulation of organic matter.

Deepening of the E horizon: breakdown or dissolution

In podzols, the E horizon deepens with time, at least during the first millennia. Current theories suggest that this deepening is due to redissolution of organic matter-metal complexes at the top of the B horizon, and reprecipitation at greater depths. Our research on podzols with deepening of the E horizon caused by improved drainage, indicates that *decomposition* of organic matter at the top of the B horizon, rather than redissolution, may be the main cause of the downward movement of the E-B boundary. Removal of metals from the top of the B may precede this decomposition (Buurman *et al.*, 2002).

TWO TYPES OF PODZOLISATION

The facts outlined above indicate the occurrence of podzols with essentially different processes of organic matter accumulation and dynamics. Although the results of these different processes are all included in the definition of the podzol-B (or spodic) horizon, we are forced to accept the existence of two different mechanisms that lead to this group of morphologies.

The first mechanism is the mobilization, transport, and precipitation of illuvial organic matter. This fits the classical theory of movement and accumulation of organic matter during the podzolisation process. The mobilization, the transport, and the precipitation part of this process are abundantly proven. Morphologically, the process leads to monomorphic illuviation cutans. Chemically, the illuviated humus should be fairly close to DOC.

The second type of podzols dominated by organic pellets. These are witness of biological activity rather than illuviation. The organic chemistry of the pellets indicates that they are dominated by root-derived material. This second type of podzols cannot be explained by the current theories. Below, we offer an explanation.

THE NEW PARADIGM

If we integrate the effect of root growth and root litter production with the current theories of mobilization, transport, and precipitation, we can account for the existence of podzols with an eluvial horizon and considerable accumulation of sesquioxides without accumulation of organic matter, and without organic coatings.

Accumulation of root-like organic matter in well drained B-horizons and deepening of the E horizon.

If organic matter in the B-horizon is largely derived from roots, it is clear that organic matter transport and precipitation plays a relatively small role. But also in such podzols, an E horizon develops, which becomes more prominent and deeper with time. If the organic matter in the B-horizon remains predominantly root-derived, this means that, with time, also the rooting zone must shift to greater depth. The formation of an E horizon implies that organic matter that had formerly accumulated in a B-horizon must disappear.

The main reason for plants to shift their largest abundance of roots to grater depth, is the occurrence of nutrients. In soils under boreal climates, and on relatively rich parent materials, considerable amounts of low-molecular-weight acids and "fulvic acids" are produced in the litter layer, but they are broken down relatively rapidly. Given sufficient percolation, such acids cause mineral weathering in the topsoil, and gradual depletion of nutrients in the uppers horizons (e.g. Melkerud *et al.*, 2000). The organic acids transport Fe and Al downward, but their breakdown causes precipitation of the transported ions, either as hydroxides, or with silica, as allophane-like substances. Downward transport of organic matter is not strong enough to cause considerable accumulation in a B-horizon, because most of the DOC is broken down. The main source of organic matter in the subsurface horizons is root litter.

If the upper layers are depleted of nutrients (e.g. of such essential elements as Fe and P, which are accumulated in B-horizons), rooting will necessarily shift to deeper parts of the profile. If roots abandon the upper horizon, organic matter from these roots is respired by microorganisms: the horizon looses its organic matter, and E-horizon develops. With time, the top of the profile will become more acidic, which slows down the breakdown of the migrating organic components. The litter continues to produce organic acids, but these are respired at greater depth in the profile, causing remobilization and deeper transport of previously precipitated secondary Fe and Al (silicate). The removal of metals, especially of Al, speeds up the decay (respiration) of (root-derived) organic matter at the top of B-horizon, so that the top of this horizon is constantly breaking down. This is a continuing process. Roots follow the nutrient front, so that they concentrate progressively deeper in the profile. In this case, B-horizon organic matter will be mainly root-derived, and illuvial organic matter will play a minor role.

If organic matter dynamics is relatively fast, accumulation of sesquioxides from overlying layers can be considerable, while organic matter accumulation is much less. This is the typical picture of zonal podzols. In absence of hydromorphic iron accumulation, only the combination of rapid organic matter dynamics and a long time of development can explain the existence of so-called Ferric Podzols or Ferrods, which have a Fe/C ratio of 6 or higher. In very nutrient-poor environments, and in systems without mesofauna activity (hydromorphic podzols), the dominance of root-derived organic matter shifts to illuvial organic matter, and turnover times are considerably longer.

CONCLUSION

Although metals (Fe, Al) in podzols are mobilized by dissolved organic components, the accumulation of metals and organic matter in B-horizons is not necessarily due to saturation of organic complexes and co-precipitation. Metals may precipitate by microbial decay of the organic carrier and be remobilized later by supply of fresh DOC. The relative abundance of root-derived and DOC-derived organic matter accumulation in the B-horizon depends on organic matter dynamics in the soil. In relatively rich soils, DOC is broken down fast by microbial activity, and is shows little accumulation in the B-horizon. In such soils, B-horizons are dominated by accumulation of iron and aluminum compounds, and by root-derived organic matter in pellet form (polymorphic organic matter). In poorer or hydromorphic soils, where breakdown of DOC is inhibited by acidity or lack of oxygen, considerable amounts of DOC may accumulate and are found in the form if monomorphic organic coatings. All transitions between the two dominant forms should exist, and single profiles might show dominance of root/derived OM in upper B-horizons and that of DOC/derived OM in the lower B-horizons. The formation of the E-horizon is mainly due to removal of metals by DOC and subsequent microbial decay of previously accumulated organic matter that has lost the protection of complexed metals.

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