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Time-dependent factors of soil and weathering mantle diversity in the humid tropics and subtropics: a concept of soil self-development and denudation

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Abstract

Time-dependent processes are the most important factor contributing to diversity of the soil and weathering mantle (SWM) in the humid tropics and subtropics. Two models of SWM self-development in time are proposed and exemplified by soil chronosequences on tropical volcanic islands in the Pacific Ocean and in the humid subtropics on the east coast of the Black Sea. The first, derived from basic ash parent material lacking phyllosilicates, is an Eutric Regosol–Vitric Andosol–Mollic Andosol–Chromic Luvisol–Humic Ferralsol sequence. The second, formed on basic material rich in phyllosilicates, is a Leptosol/Regosol–Ferrallic Cambisol–Haplic Nitisol–Stagnic Acrisol sequence. Each component of these chronosequences contributes to SWM diversity in time and space and to the complexity of the soil cover patterns. The SWM denudation model is exemplified by a Stagnic Acrisol–Haplic Nitisol–Eutric Cambisol–Lithic Leptosol chronosequence on eroded hills and terraces of the east coast of the Black Sea. Temporal and spatial changes in soil properties (texture, chemistry, mineralogy) are examined in all three SWM chronosequences. © 2001 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

The diversity of soil and weathering mantles (SWM) and the complexity of soil cover in the humid tropics and subtropics have been widely discussed (Mohr et al., 1972; Gerasimov, 1976; Young, 1976; Buringh, 1979; Soembroek, 1984; FitzPatrick, 1986; Nahon, 1986; Zonn, 1986; Sokolov, 1997). The great variety of soil properties and the different extents of weathering of the mineral material cannot be fully explained by present climatic models of soil formation. The period of soil formation and duration of pedogenesis should be considered as factors of primary importance in the SWM diversity in these areas. In areas with young relief forms of different ages (marine dunes, alluvial terraces, volcanic lava and ash mantles) the different duration of SWM development is thought to be the main factor responsible for SWM diversity (Latham, 1986; Birkeland, 1992; Quantin, 1992; Nieuwenhuyse et al., 1994; Zamotayev and Targulian, 1994a, b; Langley-Turnbaugh and Bockheim, 1997; Gracheva et al., 1998; Hugget, 1998). However, it is more difficult to estimate the role of time in determining SWM diversity on ancient denudation plains and plateaus in equatorial and tropical regions of Africa, South America, South-east Asia (Smyth and Montgomery, 1962; Dobrovolsky, 1971; Sapozhnikov et al., 1976; Seliverstov, 1976; Tardy and Roqun, 1992). Apart from the different periods of denudation and different lengths of soil development periods, certain properties inherited from pre-erosion SWM development need to be taken into account.

In this paper, we describe models of SWM development characteristic of (a) relatively young Holocene–Pleistocene surfaces and (b) more ancient surfaces, and estimate the contributions of various processes to the spatial diversity of the SWM in the humid tropics and subtropics. We consider: (1) two different pathways of parent material weathering and their effect on SWM development on silicate rocks in two areas — volcanic islands in the tropical South-west Pacific and alluvial terraces of the subtropical east coast of the Black Sea; and (2) a model of denudational evolution of the SWM in a subtropical climate on the east coast of the Black Sea.

2. Methods

Soil description and sampling sites on the studied areas were selected to minimize the variability of all soil

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factors except time. The soils were described in detail using horizon and soil nomenclature according to the World Reference Base for Soil Resources (Spaargaren, 1998).

Particle-size and chemical analyses were based on the methods of the Soil Conservation Service (1992). Thin sections were prepared from undisturbed samples and analysed for soil mineralogical and micromorphological features with a petrographic microscope. Minerals in the clay fraction ($<1\ \mu m$) were identified by X-ray diffraction using a DRON-2 diffractometer with a copper tube.

3. Two main pathways of silicate rock weathering

Soil parent rocks can be divided into two common types according to their mineralogical composition and the different processes and products of weathering:

1. Rocks containing silicates with framework and ring structure and little or no phyllosilicates. In the course of weathering these silicates are subject to congruent dissolution followed by the synthesis of allophane, kaolinite and X-ray amorphous Al and Fe oxides (Berry, 1977; Eggleton, 1987; Macias and Chesworth, 1992; Robert and Tessier, 1992; Chernyakhovskiy, 1994). Drastic losses are usually observed — up to 90% of Si and 45–60% of Al according to Chernyakhovskiy (1991) — because there are no phyllosilicates retaining the Si and Al released by weathering. This is the main reason why the SWM on such rocks is no more than a few metres thick. For example, the thickness of the SWM derived from serpentinites is only 0.05–0.5 m (Chernyakhovskiy, 1991).

2. Rocks containing phyllosilicates. In the course of weathering phyllosilicates inherited from the parent rocks (di- and trioctahedral micas, chlorites, smectites and mixed-layer minerals) are subject to incongruent dissolution producing transformation sequences typical of clays (Berry, 1977; Olives Banos et al., 1983; Macias and Chesworth, 1992; Robert and Tessier, 1992; Chernyakhovskiy, 1994). Losses are less than in the first type — up to 60% of Si and 20% of Al (Chernyakhovskiy, 1991). Retention of significant amounts of mineral substances as products of phyllosilicate transformations results in SWM profiles which are 10 m or more thick. The following zones can usually be identified within mature weathering mantles: (1) red clayey soft saprolite, including the soil; (2) yellow or brown soft/coarse saprolite; (3) greyish- or greenish-brown coarse saprolite; and (4) blocky fissured weakly changed rocks.

When studying tropical and subtropical soils confusion often arises over the difference between weathering mantle and soil or solum. Detailed discussion of the problem is beyond the scope of this paper. However, we use these terms in the following senses: the profile of a thin (1–2 m thick) weathering mantle coincides with the solum, whereas in thick mature weathering mantles the soil profile is restricted to upper layers of the mantle (no more than 3 m thick).

4. Soil self-development models

Self-development of soils is used in the sense of Rode (1947) and Yaalon (1971) for soil formation under constant climatic and topographic conditions.

4.1. Soil self-development on volcanic ash lacking in phyllosilicates

A chronosequence of soils was studied on volcanic ashes of different ages on the Tonga Islands in the South-western Pacific Ocean. The soils studied occur in well-drained parts of the volcanic topography (Niuafoou, Tofua, Kao Islands), on marine terraces of high coral atolls (Nomuka, Nomuka-Iki, Nuapapu Islands) and on terraces of Eua Island which has a fold-block relief. All the islands are covered with volcanic ashes and lavas of basaltic and andesitic/basaltic composition.

Age estimates of the ash covers vary in accuracy, those for the youngest covers (less than 1000 years) being most reliable. The ages of these young covers were estimated from historical data of recent ash falls (Bauer, 1970; Brodie, 1970; Ewart et al., 1973). The oldest ash falls were ^{14}C dated, as discussed by Orbell (1977), Leamy (1977) and Kaplin (1980).

The climate of the islands is rather uniform humid tropical; annual precipitation is 1700–2500 mm. These climatic conditions are believed to have persisted on the islands since the late Pleistocene (Gibbs, 1976; Ignatyev, 1979). The vegetation cover is represented by primary and secondary forest communities, anthropogenic grasslands and cocoa, manioc and taro plantations.

The ash cover ranges from a few cm to 2–3 m in thickness and is composed of volcanic glass ($>50\%$), clinopyroxenes (20%), basic and medium plagioclases (20%) and minor quantities of orthopyroxenes, olivine, magnetite, chalcedony and volcanic quartz.

Soils of each consecutive stage of development are (Fig. 1):

(A) The stage of Eutric Regosols (duration of pedogenesis $n \times 10$–$n \times 100$ years, horizon sequence AO–A–IIAB–IIIBC, profile thickness 30–50 cm) is characteristic of the zone of recent ash falls. The following soil-forming processes are of primary importance: organic matter accumulation, aggregation, disintegration and dissolution of volcanic glasses and plagioclases, migration of silt in suspension. Dissolution of rock-forming minerals is accompanied by desilication, leaching of Ca and Mg from the profile and synthesis of allophanes. Vertical chemical

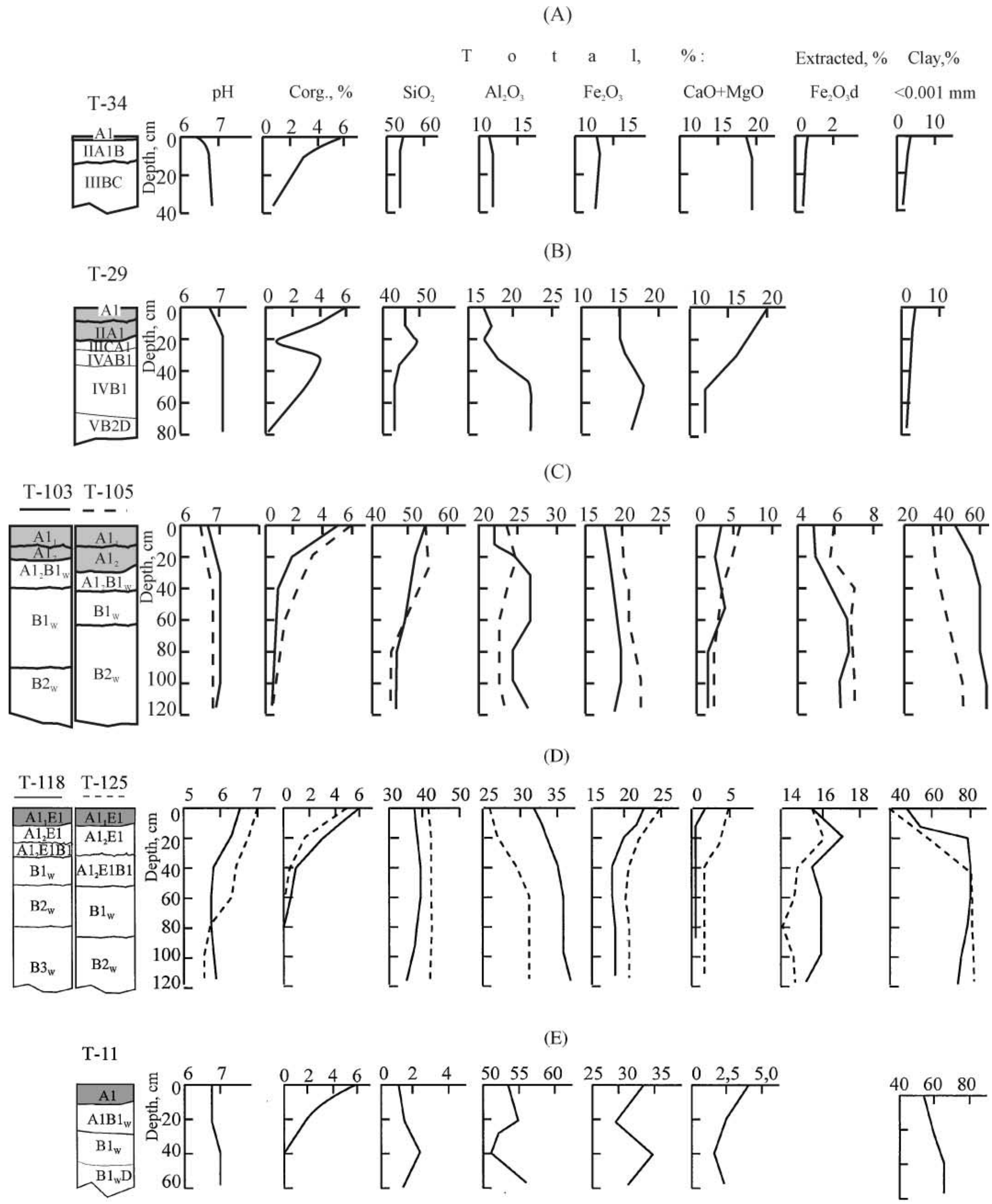

Fig. 1. The properties of soil profiles on volcanic islands in the humid tropics (South-west Pacific): (A) stage of Eutric Regosols; (B) stage of Vitric Andosols; (C) stage of Mollic Andosols; (D) stage of Chromic Luvisols; (E) stage of Humic Ferralsols; numbers above soil columns — numbers of pits; Fe_2O_3d–Fe_2O_3 extracted with citrate–dithionite–bicarbonate solution.

and mineralogical profile differentiation is not likely to occur at this stage. The content of newly formed clay particles is small and rather uniform throughout the profile.

(B) The stage of Vitric Andosols (duration of pedogenesis $n \times 100$–$n \times 1000$ years, horizon sequence AO–A–IIA–IIICA–IVAB–VB2D, profile thickness 80 cm) is common in areas with moderately recent ash falls. Leaching, desilication and synthesis of allophanes are intensified and proceed within a thicker layer than in stage A. Eluvial–illuvial differentiation of iron-humus and allophane compounds is clearly expressed. Newly formed organic and organo-mineral substances give a cloddy-granular structure impeding migration of particles in suspension.

(C) The stage of Mollic Andosols (duration $n \times 1000$–$n \times 10{,}000$ years, horizon sequence AO–A–AB1w–B1w–B2w–B2wD, profile thickness 100–120 cm) is typical of areas of thin recent ash falls. Organic matter accumulation proceeds at a slower rate than in previous stages, but volcanic glass and plagioclases have been completely dissolved. The losses of Si and Al from the solum are moderate. Of primary importance are the processes of allophane and metahalloysite synthesis and of soil aggregation, favouring vertical migration of solutions and suspensions and textural differentiation of the profile.

(D) The stage of Chromic Luvisols (duration 10,000–20,000 years, horizon sequence AO–AE1–AE1B1w–B1w–B2w, profile thickness 50–120 cm) is usual in areas of ancient ash falls. Dissolution of monoclinic pyroxenes accompanied by release of iron is complete, resulting in the formation of red-coloured allophane/oxides/metahalloysite associations of minerals. The main reserve of rock-forming minerals has been exhausted and the aggressive effect of water and humus solutions is directed towards clay minerals formed in previous stages of development. Dissolution of allophane and metahalloysite in the topsoil and illuviation of humus-iron and clay particles are active processes.

(E) The stage of Humic Ferralsols (duration of pedogenesis > 20,000 years, horizon sequence AO–A–ABw–B1w–B1wD, profile thickness 50–70 cm) is also common in areas of ancient ash falls. Allophanes and metahalloysite have been completely dissolved and a new quasi-climax association of oxides and hydroxides of Al and Fe (goethite, hematite, gibbsite, boehmite) has been formed. This leads to the progressive accumulation of ferrallitic material. No increase in profile thickness is observed because the soil is underlain by hard limestone. The solum thickness is controlled by the thickness of the volcanic ash layers.

Within the SWM self-development model proposed various groups of soils are formed, including Regosols, Andosols, Luvisols and Ferralsols. The length of life of any individual soil group is greatly affected by the age of the islands and by the frequency of the ash falls.

4.2. *Self-development of soils derived from phyllosilicate-containing rocks*

Soils were studied on alluvial terraces in the basin of the River Supsa on the eastern coast of the Black Sea. This is a region of very wet marine subtropical climate where evergreen forests were previously widespread; recently the native vegetation was replaced by tea and citrus plantations. The annual precipitation is 2000–3000 mm. A soil chronosequence was studied on terraces at four different levels. The terraces were formed during transgressions of the Black Sea and are dated at approximately 1000, 4000–5000, 100,000 and 300,000 years (Fedorov, 1963, 1971; Dobrovolsky and Urushadze, 1987). They are composed of sands and pebbles derived from post-magmatically chloritized volcanic sediments of diabase porphyrite composition.

The eastern coast of the Black Sea has experienced changes in climate and vegetation during glacial and interglacial periods. A palynological study of Black Sea sediments indicated the existence of xerophytes in this region in the late Pleistocene (Velitchko, 1973). However, coastal climatic variations were moderated by the maritime influence and the terraces were thus protected from the extremes of climate (Dobrovolsky and Urushadze, 1987).

The soils of the chronosequence are considered to be consecutive stages of soil formation and weathering, as follows (Fig. 2):

(A) The stage of Leptosols/Regosols on the first terrace level, elevation 2 m above sea level, age ~1000 years. The greyish-brown SWM profile of A–AC horizons is <40 cm thick. The soil-forming processes are accumulation of organic matter of moder type, weak aggregation and leaching in the top layer 15–20 cm thick, and accumulation of Ca and Mg as the predominant exchangeable cations. The initial sandy/pebbly material of the alluvial sediments and their stratification both remain unchanged.

(B) The stage of Ferrallic Cambisols, on the second terrace level, elevation 5 m above sea level, age — 4000–5000 years. A brown-coloured SWM nearly 100 cm thick is formed. In the top layer of the SWM a soil profile 50 cm thick has an A–Bw–BC horizons sequence. Accumulation of mull-type humus and soil aggregation are active. Leaching is more intense, leading to loss of exchangeable bases. The pebbles are almost completely destroyed, and clay occurring in the pebbles ("containers") is released and replenishes the store of fine particles throughout the soil profile. The initial stratification of the sediments has been gradually obliterated. At this stage dissolution of Ca-feldspars and pyroxenes and the accumulation of kaolinite–smectite and Fe and Al oxides occur.

(C) The stage of Haplic Nitisols–Stagnic Acrisols on the third terrace level, elevation 14 m above sea level, age ~100,000 years. A red SWM is more than 3 m thick, and the soil profile (A–AB–Bw–Btg–BC horizons) reaches ~140 cm. The content of organic matter and the thickness of humic horizons have both increased, and the loss of exchangeable Ca and Mg by leaching has been more intense. Down to a depth of 1 m all the pebbles have been completely destroyed and transformed into homogeneous fine material. Individual pebbles are visible at depths exceeding 100 cm but have been transformed into clay. Simultaneously with clay formation throughout the profile, clay has been removed from A and AB horizons and has accumulated as argillans at depths of 50–80 cm. Feldspars and pyroxenes have been nearly completely dissolved, iron has been leached and in the clay fraction kaolinite–smectite and kaolinite with imperfect structure predominate.

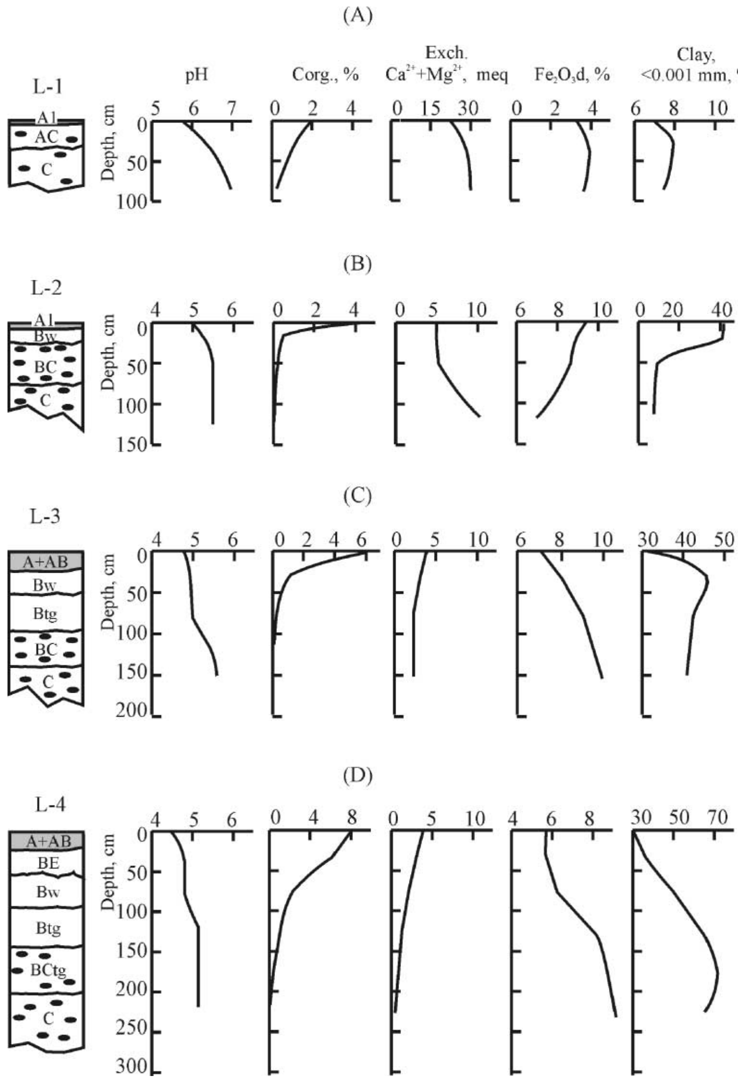

Fig. 2. The properties of soil profiles in the chronosequence of alluvial terraces in the humid subtropics (east coast of the Black sea): (A) stage of Regosols; (B) stage of Ferrallic Cambisols; (C) stage of Haplic Nitisols; (D) stage of Stagnic Acrisols. L-1, L-2, L-3, L-4 — numbers of soil pits. Fe_2O_3d–Fe_2O_3 extracted with citrate–dithionite–bicarbonate solution.

(D) The stage of Stagnic Acrisols, on the fourth terrace level, elevation 60 m above sea level, age ~300,000 years. The SWM contains zones of red soft saprolite, brown soft coarse and greyish-brown coarse saprolite and is up to 10 m thick. The soil developed within the red clayey saprolite zone with completely destroyed pebbles has a clearly differentiated profile 180–200 cm thick, with an A–AB–(E)BE–Bw–Btg–BCtg horizon sequence. Eluvial horizons and a red-white mottled zone in the subsoil are well pronounced. Acidic organic matter dominated by fulvic acids is formed, and leaching is intensified leading to drastically decreased CEC values. In spite of clay accumulation throughout the profile, clay and free iron oxides are being leached from a surface horizon 40 cm thick. In the zone of eluviation (A, E and BE horizons) feldspars and pyroxenes have been completely dissolved and kaolinite, residual quartz and dioctahedral micas are the predominant components.

Thus, on extensive terraces in the coastal regions of the Transcaucasus subtropics the soil cover is represented by Leptosols or Regosols, Ferrallic Cambisols, Haplic Nitisols and Stagnic Acrisols. The soils on terraces of other ages in the region are thought to be still more complicated.

It can be concluded that the simultaneous existence of profiles in different stages of self-development and having quite different properties is one of the most important factors contributing to the spatial diversity of soils. Changes in the soil environment and in processes of denudation are believed to result in the development of either more simple or more complicated soil covers.

5. The soil denudation model

The Neogene period in many tropical and subtropical areas was noted for repeated reorganisation of the relief, vertical tectonic movements and changes in the base level of erosion (Dumitrashko et al., 1964; Bulangje, 1987; Thomas, 1994). These processes resulted in denudation, which has often been enhanced by human activity and shifting cultivation.

The shallow SWM derived from rocks lacking phyllosilicates is most strongly affected by this erosion. As a result the soil cover pattern becomes more simple; in some areas the soil is completely washed away by the erosion, exposing hard rocks with illuviated red ferrallitic material in fissures (Chernyakhovskiy, 1991).

The effects on the thicker SWMs derived from rocks containing phyllosilicates are more complicated. The denudation of multi-horizon SWMs, especially in mountains and on dissected uplands, leads to loss of horizons to various depths. As a result deep horizons become exposed and complicated spatial patterns are formed depending upon the erosion rate and duration and upon the base level of erosion. A specific "stepped mosaic" of outcropping SWM horizons may appear, including a wide range of horizons from red clays almost unaffected by erosion to coarse saprolite and even blocky-fissured zones of the rocks. Such horizons exposed by denudation then become the parent materials for new cycles of soil formation and weathering.

The evolution of soils in the course of denudation can be exemplified by a soil sequence studied in the eastern coast of the Black Sea (Fig. 3). Several eroded surfaces in this region reflect periods of denudation during the Pleistocene (Dumitrashko et al., 1964). We examined soils occurring on different eroded surfaces derived from material of various horizons of earlier SWMs in hilly areas at heights of 400–500 m and on Middle-Pleistocene marine terraces at 180 m above sea level. The hills are made of postmagmatically chloritized diabase porphyrites. Boulders and pebbles in the terraces have the same composition.

Soils occurring on the least eroded surfaces (flattened surfaces of terraces and hill tops) and derived from red clayey soft saprolite are Stagnic Acrisols described above as the final component of the Black Sea self-development chronosequence. When affected by modern agrogenic factors the Stagnic Acrisols are subject to intense erosion. The soils of tea plantations have lost a top layer 30–40 cm thick after 50 years of cultivation, the largest soil erosion losses occurring during the initial 4–6 years of cultivation. A new humus horizon is being formed within the Bw horizon of the former Stagnic Acrisols profile. The soil profile formed by such anthropogenic denudation has properties characteristic of Haplic Nitisols.

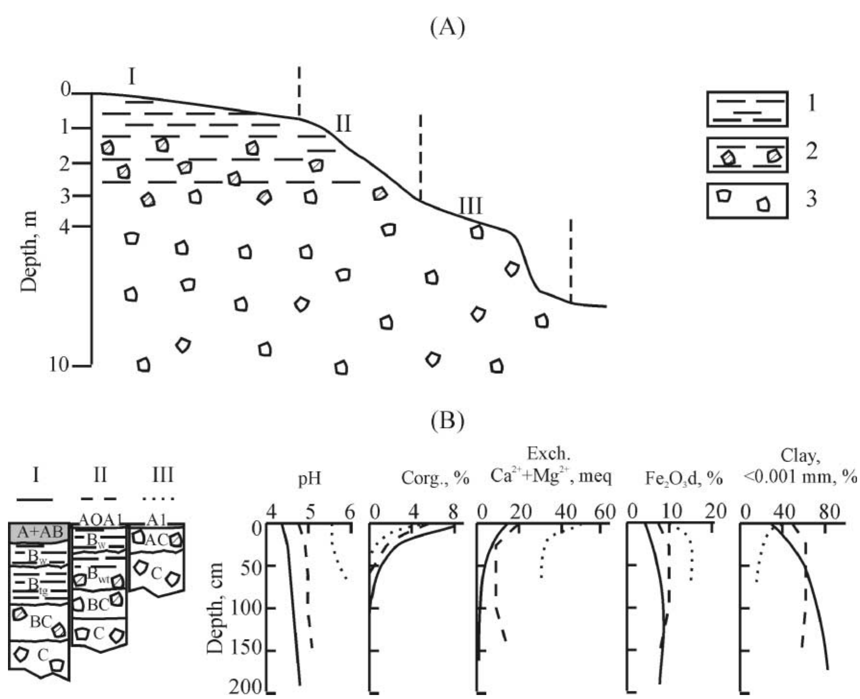

Fig. 3. The denudational sequence of soil and weathering mantle in the humid subtropics (east coast of the Black sea): (A) Distribution of soils in relation to eroded remnants of SWM: (I) Stagnic Acrisols; (II) Haplic Nitisols; (III) Lithic Leptosols: 1 — red clayey soft saprolite; 2 — red-brown soft-coarse saprolite; 3 — grey-brown coarse saprolite. (B) Properties of profiles of Stagnic Acrisols (I, continuous line), Haplic Nitisols (II, pecked line) and Lithic Leptosols (III, dotted line). Fe_2O_3d–Fe_2O_3 extracted with citrate–dithionite–bicarbonate solution.

Soils occurring on the most eroded surfaces have thin profiles (0.6–1.0 m), low organic matter contents, grey and brown colours and relatively coarse texture inherited from the zone of coarse saprolite. The soil properties reflect the low degree of weathering of the initial material; residual corroded grains of primary minerals are common and smectites, chloritized smectites and chlorites formed by post-magmatic processes dominate the clay fraction. The properties of such soils depend upon the degree of erosion but are similar to those of Eutric Cambisols or Lithic Leptosols.

Thus the combined processes of development, long-term natural and human-induced erosion, exposure of deep horizons of SWMs and inheritance of their properties by recent soils together with post-denudation pedogenesis have resulted in formation of a wide spectrum of soils in the Transcaucasian humid subtropical area. This spectrum includes Stagnic Acrisols, Haplic Nitisols, Eutric Cambisols and Lithic Leptosols.

6. Conclusions

1. Time-dependent patterns of SWM formation in the humid tropics and subtropics have been established based on studies of soil chronosequences on volcanic islands of the South-west Pacific Ocean and on the east coast of the Black Sea.

2. Two models of SWM development in time and space controlling their diversity — self-development and denudational — are proposed.

3. Different models of SWM self-development have developed in areas with different soil-forming materials. In the Tonga Archipelago SWM development on volcanic ashes has formed the following soil chronosequence: Eutric Regosols–Vitric Andosols–Mollic Andosols–Chromic Luvisols–Humic Ferralsols, the age of the SWMs ranging from $n \times 10$ up to $> 20{,}000$ years. On the east coast of the Black Sea on river terraces composed of weathered products of chloritized diabase porphyrite quite different SWMs have been formed, and the chronosequence consists of Leptosols/Regosols–Ferrallic Cambisols–Haplic Nitisols–Stagnic Acrisols, the age ranging from < 1000 to 300,000 years.

4. A denudation model of SWM development was studied on eroded hills and terraces of the east Black Sea coast. Neogene denudation and post-denudational pedogenesis have formed the following spatial-temporal soil sequence: Stagnic Acrisols–Haplic Nitisols–Eutric Cambisols–Lithic Leptosols.

5. The models of SWM development proposed are believed to be widely distributed in tropical and subtropical areas. Soil self-development models explain the spatial diversity of soil cover on relatively young surfaces, such as areas of Holocene–Pleistocene volcanic activity and on alluvial terraces of different ages. Soil denudation models are applicable to older surfaces, which have undergone repeated erosion cycles and to mountain areas with strong tectonic activity.

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