ISSN 1064-2293, Eurasian Soil Science, 2010, Vol. 43, No. 6, pp. 601–613. © Pleiades Publishing, Ltd., 2010.
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GENESIS AND GEOGRAPHY OF SOILS

Soil Development on the Crimean Peninsula in the Late Holocene

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Received March 26, 2009

Abstract—The study of soils of different ages in different physiographic regions of the Crimean Peninsula made it possible to reveal the main regularities of pedogenesis in the Late Holocene (in the past 2800 years). With respect to the average rate of the development of soil humus horizons, the main types of soils in the studied region were arranged into the following sequence: southern chernozems and dark chestnut soils > mountainous forest brown soils > gravelly cinnamonic soils. In the newly formed soils, the accumulation of humus developed at a higher rate than the increase in the thickness of humus horizons. A sharp decrease in the rates of development of soil humus profiles and humus accumulation took place in the soils with the age of 1100–1200 years. The possibility for assessing the impact of climate changes on the pedogenetic process on the basis of instrumental meteorological data was shown. The potential centennial fluctuations of the climate in the Holocene determined the possibility of pulsating shifts of soil-geographic subzones within the steppe part of the Crimea with considerable changes in the rates of the development of soil humus horizons in comparison with those in the Late Holocene.

DOI: 10.1134/S1064229310060013

INTRODUCTION

The dependence of the geographic distribution of zonal soil types of continental plains on climatic conditions was clearly formulated by Dokuchaev in 1899. Since then, this problem has been studied in detail. In the context of modern climate changes, the history of soil development in the Late Holocene (without taking into account the previous history) and its chronological regularities acquire special significance.

Generalization of soil-geographic materials on various climatic zones made it possible to suggest the models of pedodiversity in each particular type of climate; these models can be considered as the models of records of the particular climatic conditions in the memory of different soils [25]. Among the factors leading to the development of diverse soils and soil features under similar climatic conditions, the factor of chronological diversity of the soils should be mentioned. It is conditioned by the creation of the anthropogenic surfaces of different ages, for which the zero moment of pedogenesis can be determined.

For a correct interpretation of relationships between soils and climate, two methodological problems have to be solved. First, we have to determine the possibility for extending data on the bioclimatic potential of modern soil-geographic zones (subzones) into the past, i.e., into the history of soil formation that has specified the formation of diagnostic soil features. Second, we have to take into account significant differences in the characteristic time of the formation of humus profiles of chernozems and the entire duration of the Holocene pedogenesis; this difference manifests itself in the development of polygenetic soil profiles. These problems can partly be solved via studying soil evolution on the basis of data on the particular time periods of soil development.

The problem of the time factor in soil formation was also formulated by Dokuchaev. In recent decades, a new branch of pedology—archaeological pedology—has been shaped. It studies modern surface soils and paleosols buried under archaeological monuments of different ages dated by the archaeological methods [7]. The study of surface soils developed on the surfaces of archaeological monuments of different ages is also highly informative. Spatial sequences of the soils of different ages may be considered as the models reflecting the stages of soil evolution in time [5].

The analysis of temporal changes in soil–climatic relationships [30] demonstrated that the value of the soil profile index considerably increases with an increasing age of the soils, though this increase does not depend on the particular climatic conditions of soil development. In the new substantive-genetic classification of Russian soils, facial subtypes of soils are not distinguished, because "the specificity of climatic conditions and soil regimes are not always recorded in the soil profiles" [14, p. 53]. For example, southern chernozems of the south European (Cis-Caucasian facies) facies developed under the barrier effect of the Caucasus [2] do not have their analogues in the new soil classification [14].

The Crimean Peninsula is characterized by a specific spectrum of latitudinal and vertical soil zones. It represents a valuable research polygon for studying soil geography in relation to climatic conditions. In the Neogene and Quaternary periods and, particularly, in the Holocene, the more ancient mountainous forest landscapes of the Crimean Mountains got in direct contact with the younger landscapes of plain Crimean steppes [8]. Owing to the barrier effect of the Crimean Mountains, the inverse pattern of latitudinal soil zones [18] is observed within the northern plain part of the peninsular. Landscapes of desert steppes, dry wormwood–grassy steppes, and moderately dry true forb–grassy steppes replace one another from the northern part of the Crimea (Perekop) to the south, up to the northern macroslope of the Crimean Mountains. At a distance of 140 km, arc-shaped zones of dark chestnut soils, southern chernozems, and calcareous and leached piedmont chernozems replace one another in the same direction. At the foothills, at the height of 400–450 m a.s.l., mountainous gray forest soils are developed. However, the history of the development of Crimean soils with time remains poorly studied. To restore this history, new original empirical data are required.

OBJECTS AND METHODS

The diversity of soils on a relatively small territory of the Crimean Peninsula (25880 km^2) is very great. There are 51 soil units in the systematic list of Crimean soils [22]; they belong to 18 genetic soil groups. Anthropogenically transformed soils and soils developed on cultural layers of different ages are widespread in Crimea. Thus, it is possible to study the spatiotemporal models of pedogenesis [5] on dated surfaces of various archaeological monuments: ancient ramparts, settlements, burial mounds, etc.). In the recent studies of soil evolution, the method of studying the soils of different ages developed from similar substrates under similar bioclimatic conditions and arranged into chronological sequences has become one of the major methods. In order to understand the regularities of soil development with time, it is necessary to obtain the chronological soil functions, i.e., to trace changes in the given soil properties on the time scale established by quantitative dating methods (archaeological, radioisotopic, historical, etc.). The experience on dating soil horizons buried under ancient ramparts on the Crimean Peninsula [17] demonstrated that ^{14}C data may be correlated with the periods of certain archaeological cultures in general. However, the determination of narrower periods with a necessary accuracy requires the application of some other methods; multiple investigation methods should be used to study buried and surface soils of different ages.

The list of officially recognized archaeological objects in Crimea includes 4420 names; taking into account separate monuments within the given archaeological sites, it includes 9137 names. The first anthropogenically transformed areas with a cultural layer appeared in Crimea in the second part of the fourth and at the beginning of the third millennium BC, during the Latest Neolithic and Bronze epochs (the Latest Neolithic culture is known under the name of "shell mounds.") After the Early Iron epoch, from the 8th century BC to the 4th century AD, the Cimmerian, Kizil-Kobinsk, Taurus, Scythian, and Antique cultures existed in Crimea. The medieval epoch (from the 5th to the 17th century AD) also left its archaeological records in this region. Each of these cultural periods was marked by the appearance of new objects, on which newly formed soils of different ages were developed.

Our pedochronological investigations included various dated archaeological objects (settlements, ramparts, and kurgans) in the range from the 14th century BC to the 9th century AD; soddy surfaces developed in trenches, on dump rocks, and on other technogenic surfaces dating back to the 15th–20th centuries AD were also studied. For a comparison, data on the morphology and properties of the full-profile Holocene soils were analyzed. The location of major objects of our study is shown on Fig. 1. The physiographic subdivision of the Crimean Peninsula is given according to [23]. Overall, more than 60 objects were studied. A larger part of the obtained soil-chronological data corresponds to the Subatlantic period of the Holocene, i.e., to the past 2500 (according to Blytt–Sernander) or 2800 [1] years.

The morphology of soil profiles on dated archaeological surfaces was performed in soil pits displaying the sequence of newly formed soil horizons. Valuable information on the location and dating of various archaeological monuments, including antique monuments, in the area of Kerch was obtained from Dr. Sci. (History) V.N. Zin'ko [9]. Probable errors in dating of the objects (settlements, ramparts, and kurgans) created by the cultures of the Iron Age range from 25 to 50 years.

For modeling the development of soil humus horizons with time, the observed thickness of the humus layer (A + AB horizons) was corrected for the equilibrium bulk density (1.15 g/cm^3). The soil color was determined according to Munsell color charts.

Soil analyses were performed by standard methods; the humus content was determined by Tyurin's method; the bulk nitrogen content, by Kjeldahl's procedure; the CO_2 of carbonates, by the acidimetric methods; the hydrolyzable nitrogen, by the Tyurin–Kononova method; and the available phosphorus and potassium, by the Machigin method (in the TsINAO modification).

Meteorological observations in Crimea have been performed in 65 places, including 20 permanent weather stations. Data on the mean annual precipitation and radiation balance of the surface covered by grasses in the summer and by snow in the winter (as

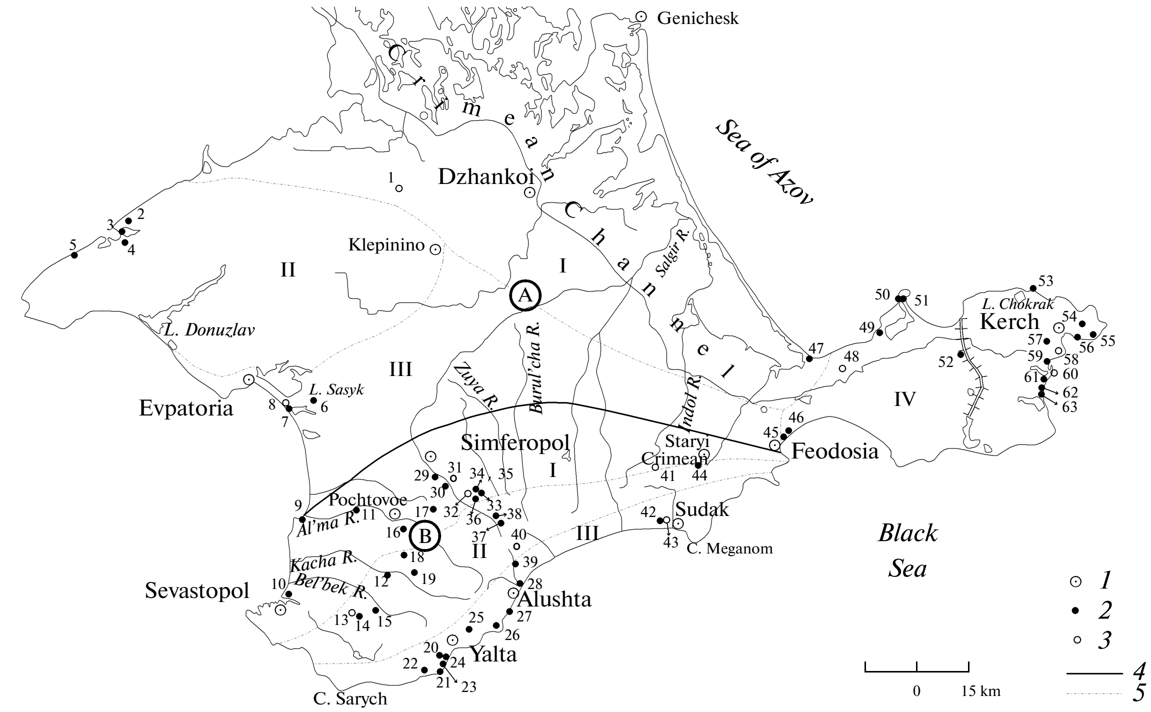

Fig. 1. Objects of pedochronological investigations: (*1*) present-day settlements, (*2*) soils of archaeological monuments, (*3*) soils on disturbed surfaces, (*4*) landscape boundary between the plain steppe Crimea (A) and the Crimean Mountains (B), and (*5*) boundaries of climatic regions (see Table 4). Dated soil objects: (1) Grishino, quarry stripping; (2) Mezhvodnoe, settlement; (3) Panskoe, estate; (4) Yarylgach, settlement; (5) Kalos-Limen, ancient town; (6) Garshino, settlement; (7) Kara-Tobe, ancient town; (8) Evpatoria, pillbox; (9) Ust'-Al'minsk, settlement; (10) Chersoneses, wall; (11) Alma-Kermen, settlement; (12) Syuren, fortress; (13) Kholmovka, trenches; (14) Eski-Kermen, cave city; (15) Mangup, cave city; (16) Bakla, cave city; (17) Tash-Dzhargan, settlement; (18) Chufut-Kale, cave city; (19) Kyz-Kermen, cave city; (20) Krestovaya Mt, settlement; (21) Ai-Todor, monastery; (22) Issar-Kaya, fortress; (23) Kharaks, Roman wall; (24) Kharaks, rampart; (25) Gelin-Kaya, fortress; (26) Artek, settlement; (27) Plak Cape, church ruins; (28) Aluston, fortress; (29) Krasnoe, settlement; (30) Scythian Naples, settlement; (31) Simferopol, dump rock; (32) Simferopol, dump rock; (33) Dzhalman, settlement; (34) Dolgorukovskaya Yaila, settlement; (35) Druzhnoe, settlement; (36) Pionerskoe, settlement; (37) Kizilkobinskoe, settlement; (38) Mamut-Sultan, settlement; (39) Funa, fortress; (40) Demerdzhi, trenches; (41) Toplovskii Monastery (ruins); (42) Sudak fortress (14th century); (43) Sudak fortress, ruins of quarters (18th century); (44) Surb-Khach, monastery; (45) Feodosia, Kaffa (fortress wall); (46) Aivazovskoe, water delivery system; (47) Arabatskaya fortress, ruins; (48) Semisotka, trench; (49) Semenovka, settlement; (50) Mesovka (Mysovoe II), settlement; (51) Heraclium, settlement; (52) Uzunlar, rampart; (53) Zyuk Cape, Zenon Chersoneses, settlement; (54) Kamenka, settlement; (55) Enikale, fortress; (56) Mirmekii, ancient city; (57) Kerch, kurgan (to the north of the second Zmeinyi kurgan); (58) Kerch, fortress (19th century); (59) Tiritaka, ancient city; (60) Kerch, Arshintsevo district, dam; (61) Nymphaion, ancient city; (62) Geroevka II, settlement; (63) Geroevka I, settlement. (A) Crimean steppe province: I—North Crimean Lowland steppe, II—Tarkhankut elevated plain, III—Central Crimean plain steppe, and IV—Kerch hilly–ridged steppe. (B) Crimean Mountains: I—foothill forest-steppe; II—main ridge, mountainous meadows and forests; and III—southern coast.

measured at the actinometrical stations) have been obtained from reference books [15, 24]. Upon studying the geographic regularities of energy expenses on soil formation in different regions, the amount of available data on the radiation balance (*R*) is much smaller than the amount of data on the temperature and precipitation, because only some of the weather stations perform actinometrical observations. To compensate for this gap, we have used a statistical dependence between *R* values and the accumulated air temperatures >10°C calculated on the basis of climatic data on the East European Plain. The relative error of this estimate does not exceed 10%. Though this approach has a tentative character, it allows us to judge the geographic regularities of heat supply of soil formation. To ensure the continuity of long-term weather data, some missed data were restored on the basis of data on the analogous weather stations.

A schematic map showing the distribution of radiation energy expenses on soil formation (*Q*) was built in the ArcInfo system with the Spatial Analyst module. To create the grid, the regular spline function with the weight of a point of 0.1 and the number of points equal to 12 was used. Data from weather stations beyond the Crimean Peninsula were also used, which made it possible to ensure a better accuracy of drawing of the iso-

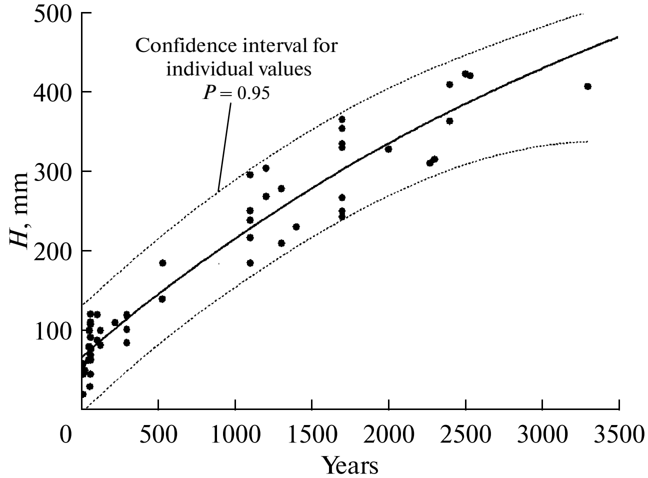

Fig. 2. Thickness of the humus horizon (H, mm) in southern chernozems and dark chestnut soils as dependent on their age.

lines of Q. On the basis of this map, the areas with different Q values were calculated.

RESULTS AND DISCUSSION

Soil Formation in the Late Holocene

In order to reveal regularities of the formation of humus horizon and humus accumulation as dependent on the age of soils, the morphology and physicochemical properties of soils developed on the anthropogenically disturbed surfaces were studied. These surfaces were dated by the archaeological methods; their ages ranged from 3300 to 20 years. The investigated objects were found in the areas of the major zonal soils of the Crimean Peninsula, including chernozems (>45% of the area of the peninsula) and chestnut soils on plain territories and mountainous brown forest and cinnamonic soils. Specific soils formed on the cultural layer of ancient settlements were also studied [22]. Selected data on the contents and reserves of humus in the main genetic groups of soils of different ages are given in Table 1, and the chemical properties of the studied soil chronosequences are given in Table 2.

Soil ontogenesis is a nonlinear process; it is characterized by a complex sequence of nonequilibrium dynamic transitions toward the equilibrium (climax) state. The development of the main morphological attribute of chernozemic soils—their humus horizon—proceeds through several stages. At the initial stage, rapid in situ humus accumulation takes place; then, a longer stage of the eluvial–illuvial processes is observed [29].

To obtain the chronological function from data on the chronosequence of surface soil, the appropriate analytical function has to be found. As shown earlier [29], the process of self-development of soil as a bioabiotic system can be adequately described by the models of growth successfully applied in the studies of various biological and ecological systems.

The dependence of changes in the thickness of humus horizon with time t (H_t) can be described by an exponential function

$$H_t = H_{\lim}(1 - k \cdot e^{-\lambda t}), \quad (1)$$

where $H_{\lim}$ is the limiting (maximum) thickness of the humus horizon, k is the index characterizing the level of initial fertility of the parent material in zero moment of soil formation, and λ is an empirical coefficient reflecting the bioclimatic conditions (yr^{-1}).

It should be noted that pedochronological data on the first centuries of pedogenesis in the studied soil chronosequence could be conventionally attributed to the beginning of the Late Holocene (the Subatlantic phase); the bioclimatic conditions in that period could differ from the modern bioclimatic conditions.

The dependence of the thickness of humus horizons of soils in the steppe zone on the relative age of these soils (Fig. 2) has been obtained on the basis of data on 56 soil objects on dated surfaces of the Kerch Peninsula [6] and additional data on soils developed on the Crimean Plain. We failed to find reliable differences in the thickness of humus horizons for the soils that developed in the past 2600 years in the zones of southern chernozems and dark chestnut soils.

The approximation of pedochronological data reflecting the conditions of soil formation on loose parent materials in the steppe part of the Crimean Peninsula (Fig. 2) according to Eq. (1) made it possible to obtain the following model of changes in the thickness of humus horizons (H_t, mm) with time (t is the soil age, years):

$$H_t = 800(1 - 0.917e^{-0.00023t}). \quad (2)$$

This model makes it possible to refine the estimates obtained on the basis of studying buried soils. In the Subatlantic period, the thickness of humus horizon has been increasing at the rate of 10 mm per century, or remained stable [11]. According to model (2), the average rate of the formation of soil humus horizons in the steppe zone of Crimea during the Late Holocene (2.8 ka) is estimated at 12.3 mm/100 yrs. Taking into account the nonlinear character of the dependence $H_t = f(t)$, it is reasonable to determine the critical zone of a radical change in the rate of this process. It takes place within the interval of 1100–1200 yrs. Taking this into account, we may estimate the average rate of the development of soil humus horizons in the first 1200 years at 14.7 mm/100 yrs; in the second part of the studied chronointerval (1200–2500 yrs), it decreases to 11 mm/100 yrs.

A regular increase in the thickness of humus horizons in the newly formed soils during 2800 years has been accompanied by corresponding changes in the qualitative and quantitative characteristics of soil humus.

Table 1. Contents and reserves of humus in the humus horizons of the soils of different ages

Study object	Soil age, years	Thickness of humus horizon, mm	Humus content, %	Bulk density, g/cm^3	Humus reserves, t/ha
Southern chernozems and dark chestnut soils					
Kaffa, fortress wall	532	140	4.94	0.90	60.3
Zyuk Cape, Chersonesos	1300	230	4.86	0.86	96.1
Heraclium, settlement	1700	310	6.08*	1.20	223.8
Kerch, kurgan	1700	315	2.99	1.20	111.2
Uzunlar rampart	2000	310	3.04	1.16	109.4
Calcareous chernozems, piedmont chernozems, and soddy calcareous soils					
Simferopol, dumped earth	10	30	8.40	1.28	32.2
The same	50	60	6.60	0.90	35.6
Chufut-Kale, cave city	300	50	5.33	0.95	25.3
The same	600	80	8.45	0.95	64.2
The same	650	50**	5.45	0.95	25.8
Pionerskoe, mosque ruins	500	65	5.27	0.95	32.5
Semenovka I, settlement	1720	310	4.72	0.95	139.9
The same	1720	160**	3.78	0.96	58.1
Kalos-Limen, settlement	1800	336	4.77	0.93	149.0
Scythian Naples	1800	280	7.70	0.90	194.0
Mamut-Sultan, settlement	1800	305	5.74	1.07	187.3
The same	1800	330	4.91	1.23	199.2
Panskoe, estate	2270	230**	2.60	1.20	71.8
Ashy soils (cultural layer)					
Mysovoe II, settlement	1100	220	6.08*	0.88	117.7
Heraclium, settlement	1700	440	4.80*	0.92	189.0
Brown mountainous forest soils					
Mekenziev Mounts, trenches	57	60	8.20	1.01	49.7
Eski-Kermen, ruins of cave city	700	60**	8.10	1.00	48.6
The same	700	80	6.27	1.00	50.2
Cinnamonic soils					
Mount Krestovaya, settlement	500	135	8.40	1.20	136.8
Funa, fortress	500	145	5.94	1.20	103.4
The same	500	180	6.35	1.20	137.2
Cape Ai-Todor, monastery ruins	1000	155	2.20	1.20	40.9
Kharaks, Roman wall	1600	310	6.33	0.63	123.6
The same	1600	190**	10.08	0.74	141.7
Kut-Lak, settlement	2000	300	7.70	1.00	231.0

Notes: * Including carbon of nonhumus compounds.
** The soil was formed on the limestone plate.

Table 2. Soil properties on dated surfaces

Study object	Texture*	Soil age, yrs	Horizon; depth, cm	Humus, %	Water-extractable humus, %	N, %	C : N	Total acidity, meq/100 g soil	N	K_2O	P_2O_5
									mg/100 g		
Kerch, dump rock of the limestone deposit	Cl	15	A, 0–2	2.53	Not det.	0.168	8.7	Not det.	99.4	640	30.1
			AC, 2–5	1.96	0.064	0.195	5.8	″	63.0	560	21.0
Geroevskoe, bank of a trench	Gr. l	61	A, 0–7	4.17	Not det.	0.383	6.3	0.86	233.8	1440	116.1
			AB, 7–12	3.47	0.061	0.360	5.6	Not det.	145.6	940	32.2
The same place, breastwork	Ml	61	A, 0–6	3.47	0.097	0.300	6.7	″	11.2	900	28.7
			AB, 6–9	5.41	0.081	0.383	8.2	″	131.6	840	12.2
The same place, railroad levee	Gr. l–S	105	A, 0–6	3.28	0.067	0.388	4.9	0.52	145.6	640	70.5
			AB, 6–10	3.77	Not det.	0.218	10.0	0.45	78.4	500	65.5
Enikale, fortress, upper castle	Gr. l	300	A, 0–6	3.37	0.069	0.296	6.6	0.24	233.8	940	121.5
			AB, 6–11	3.39	0.094	0.375	5.2	0.32	77.0	940	48.7
Enikale, fortress	Ml with fine limestone gravel	300	A, 0–7	6.70	0.036	0.283	13.7	Not det.	190.4	640	23.5
			AB, 7–13	5.03	0.083	0.383	7.6	0.39	151.2	560	12.0
			B1, 13–24	3.28	0.103	0.325	5.8	0.35	86.8	342	4.3
Geroevka I, settlement	Ml	1100	A, 0–14	4.30	0.075	0.373	6.7	Not det.	130.2	800	65.9
			AB, 14–24	2.29	0.056	0.242	5.5	0.30	65.8	840	42.9
			BC, 24–51	2.18	0.061	0.320	3.9	0.27	60.2	900	57.2
Mirmekii, town	Gr. l	1300	A, 0–13	6.79	0.058	0.313	12.6	Not det.	256.2	640	92.2
			AB, 13–27	5.30	0.103	0.298	10.3	″	137.2	700	82.7
Nymphaion	Ml	2300	A, 0–18	5.72	0.086	0.368	9.0	0.78	224.0	1780	133.1
			AB, 18–50	4.44	0.083	0.145	17.7	0.43	116.2	1640	91.6
			BC, 50–74	2.69	Not det.	0.465	3.3	Not det.	50.4	1680	114.4
Kamenka, Late Bronze settlement	Hl	3300	A, 0–23	4.68	0.075	0.335	8.1	″	152.6	1340	76.1
			AB, 23–40	3.39	0.078	0.375	5.2	″	106.4	1000	18.7
			B1, 40–56	3.33	0.050	0.275	7.0	″	105.0	800	34.3
Virgin soil	Hl	10000	A', 0–24	2.77	0.050	0.300	5.3	0.31	98.0	340	6.6
			A'', 24–42	2.07	Not det.	0.373	3.2	Not det.	71.4	224	7.1
			AB, 42–67	1.29	″	0.260	2.9	0.29	60.2	168	4.8
			B1, 67–84	1.00	0.033	0.343	1.7	0.27	32.2	154	2.3

* Texture groups: Ml, medium loam; Hl, heavy loam; Cl, clay; Gr. l, gravelly loam, and S, sand.

It should be noted that the cultural layers usually contain some amounts of the allochthonous organic carbon, which leads to some overestimation of the results of pedogenesis. At the same time, some time gap between the age of artifacts found in the cultural layer and used to determine its age and the time of the beginning of soil formation on the surface of the cultural layer means that the age of the soils is somewhat overestimated, i.e., that the rates of the development of soil humus horizons are underestimated. Also, it is known that some amounts of organic matter are present in the natural parent rocks; thus, marl and chalk deposits content up to 0.2% of C_{org}; red-brown clay, 0.32%; loesslike loam, 0.3–0.5%; and true loess, up to 0.65–0.75%.

The interdependence of the growth of soil humus horizons and humus accumulation processes in the studied soils is displayed on a separate plot (Fig. 3). The limiting (maximum) values of the thickness of soil humus horizons and the reserves of humus in them typical of the particular types and subtypes of Crimean soils have been obtained from the previously generalized data on the morphology and properties of these soils [16, 19, 20].

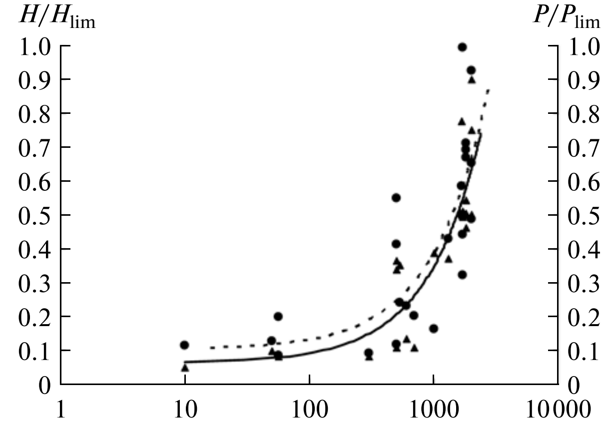

Fig. 3. Changes in the pools of humus and thickness of humus horizons in Crimean soils: (*1*) factual thickness of humus horizon normalized for its limiting value (H/H_{lim}), (*2*) factual data on the humus pool normalized for its limiting value (P/P_{lim}), and (*3*) and (*4*) approximation curves for the thickness of humus horizons and humus pools, respectively.

The reserves of humus in the initial 2000 years of the humus profile development increase from 50 to 300 t/ha. The process of humus accumulation is faster than the process of the downward development of the humus horizon, which is particularly well pronounced in cinnamonic soils developed from hard parent materials. In general, the development of soil humus profiles is characterized by a relatively quick achievement of a quasiequilibrium status (with respect to the humus content and the thickness of humus horizons). This may be explained by the high mobility of the newly formed organic matter in the soil profiles under conditions of a considerable soil moistening in the wet seasons. A long-lasting frostless period (170–270 days) and a high efficiency of precipitation (73–88% of annual precipitation is absorbed by the soils) are typical of the Crimean Peninsula.

A period of a sharp deceleration of the downward development of soil humus horizon and humus accumulation is observed upon reaching the quasiequilibrium state at the age of 1100–1200 years.

The high enrichment of humus with nitrogen typical of the initial period of soil formation changes to the moderate enrichment of humus with nitrogen (C : N = 8–10) at the soil age of 1000–3000 years; in the mature Holocene soils, the C : N ratio decreases again to 5.3. The portion of water-soluble humus decreases from 3% in the young soils to 1.8% in the mature soils; as a rule, it is higher in the AB horizon in comparison with the A horizon.

In the mature chernozems, the coefficient of phosphorus accumulation in the upper humus horizon (the ratio of the bulk phosphorus content in the layer of 0–25 cm to its content in layer of 100–180 cm) is 1.22. In the first 2000 years of pedogenesis, the content of available phosphates in the humus horizon increases by 4.5 times; then, it somewhat decreases. In the soils developed from the substrates, in which the redistribution of phosphorus can be due to the action of root systems, the coefficient of accumulation of available phosphorus in the upper humus horizon generally increases from 1.1–1.4 in the young soils to 3.0 in the full-Holocene soils.

The cultural layers of archaeological monuments are enriched in carbonate minerals. Under conditions of a relatively mild Crimean climate, these carbonates are subjected to intense leaching already in the first decades after the beginning of soil formation. In 1000–1500 years, the degree of leaching of carbonates from the soil profiles reaches its maximum. The studied soils are characterized by an alkaline reaction, and the changes in their pH conditions with time are weakly pronounced. This is explained by the geochemical specificity of the landscape affected by the alkaline ions of sea aerosols against the background of the high alkalinity of parent materials.

Mountainous brown forest soils developed from the eluvium of hard rocks are characterized by the lower rates of the growth of their humus horizons; the average rate in the first 700 years is estimated at 11 mm/100 yrs.

Though the area occupied by the mountainous cinnamonic soils in Crimea is relatively small (about 2%), their areas are of particular interest. These soils are developed within the northernmost periphery of Mediterranean landscapes protected from the invasions of cold air masses from the north by the Crimean Mountains with the heights of 1200–1500 m a.s.l. The character of pedogenesis under conditions of Mediterranean climate is controlled by the specificity of the soil temperature and moisture regime in the wet and relatively warm winter. The weakening of organic matter mineralization processes in the summer favors the polymerization of humic substances and their preservation in the soil profile. As a result, cinnamonic soils developed from the eluvial and colluvial derivatives of hard bedrocks under the evergreen xerophytic forests and shrubs have the humus layer of 70–80 cm in thickness with the high (7–10%, in some cases, up to 13%) content of humus and the high content of carbonates in the entire profile. Little is known about the development of these specific soils with time.

Interesting data have been obtained during the pedochronological studies in the area of the Kharaks archaeological monument on the Ai-Todor Cape. This ancient settlement was founded by Romans and existed in the first–fourth centuries AD. The outer perimeter of this settlement was encircled by a rampart composed of large limestone blocks and clayey material; the width of this rampart was 2.2–2.4 m. The inner wall built of limestone is also partly preserved. It is known that cinnamonic soils are developed in Crimea both from calcareous and noncalcareous materials. In this context, the presence of these two archaeological objects built at approximately the same time and in the same place is of great interest. The properties of cinnamonic soils that developed on the outer rampart from the clay substrate and on the inner wall from the eluvium of Jurassic limestone are given in Table 3.

As shown in [31], the development of the upper dark-gray humus horizon (AU) of cinnamonic soils with time is described by the following model:

$$H_t = 400(1 - 0.674e^{-0.00022t}), \quad R = 0.683. \tag{3}$$

During the first 2000 years, the humus horizon of 21–25 cm in thickness is formed. It has a dark brown color or brown-gray color in the upper part and a reddish dark brown color in the lower part and very fine granular structure. The organic matter content reaches 8.3–8.7%; the content of nitrogen is higher in the soil developed from the noncalcareous (clayey) parent material.

The function described by Eq. (3) indicates that the average rate of the development of humus horizon in the gravelly cinnamonic soils during the first 2000 years of their development is about 4.7 mm/100 yrs; the average rate of the humus accumulation is about 0.6 t/yr.

The soils developed from the cultural layer of ancient settlements occupy a special place in the regional classification of Crimean soils [22]. Their area is estimated at 14200 ha (in the Ukrainian soil classification system [19], these soils were excluded from the general system; the cultural layers were classified as specific rock outcrops). The soils developed from the cultural layer in 1100–1700 years have a distinct dark gray humus horizon of 21–28 cm in thickness and a light gray transitional horizon. The soil reaction in the humus horizon is alkaline (pH 8.2–8.8); in the initial substrate (cultural layer), it is strongly alkaline. The humus content in the upper horizon reaches 6–7%, though some amounts of organic carbon in this horizon may be inherited from the specific parent material (cultural layer), i.e., it has a nonhumus nature. The bulk nitrogen content is significant (0.40–0.49%), and the C : N ratio in the soil humus is moderate (8.2–8.8).

Climatic Factors of Pedogenesis

The nonlinear dependence of the rate of soil formation on the climatic indices (heat and water supply) should be taken into account. This is one of the reasons for a relatively low efficiency of correlations between soils and climatic characteristic upon the use of some integral climatic indices and simple indices of the heat and water supply in different soil-geographic zones. From my point of view, the ideas of the bioenergetics advanced by V.R. Volobuev yield much promise for further studies. Volobuev [4] estimated the efficiency of pedogenesis with the Q function determined by his as the annual expenditure of radiation energy of soil formation. After the correction of the initial equation [4] for the units of the international system of units, the Q value (in MJ/m^2) can be calculated as follows:

$$Q = 41.868\left[R \cdot e^{-18.8\frac{R^{0.73}}{P}}\right], \tag{4}$$

where R is the radiation budge (kcal/cm^2 per year) and P is the annual precipitation, mm.

It is known that the depth of the active pedogenesis is largely controlled by the seasonal dynamics of hydrothermal conditions with alternation of the period of intensive soil moistening in the winter and early spring (in the Crimean mountains, it also takes place in the fall) and the period of soil drying in the summer. The recently suggested grouping of Ukrainian soils [21] with respect to the soil profile thickness was established on the basis of data on the amount of precipitation utilized by the soils. In our calculations (Table 4), efficient precipitation (precipitation absorbed by the soil) is equal to the annual precipitation minus precipitation in the hot (>20°C) summer period. As seen from Table 4, the most efficient use of precipitation (up to 82–88%) in the course of soil formation is observed in the piedmont forest-steppe zone and in the western part of the Mediterranean area.

A more detailed pattern of the spatial differentiation of Crimean soils as dependent on the climatic conditions may be obtained from the analysis of energy expenses on soil formation (Fig. 4).

Table 3. Some properties of 1600-year-old cinnamonic soils on the walls of the Roman Kharaks Fortress

Soil properties	Inner wall			Outer wall	
	humus horizons and their depths, cm				
	A', 0–5	A'', 5–16	AB, 16–31	A', 0–5	A'', 5–16
Soil color (Munsell scale)					
dry state	10YR3/2	10YR3/2.5	10YR4/2	5YR3/2	5YR3/3
wet state	7.5YR3/1	7.5YR3/2	7.5YR3/2	7.5YR3/2	5YR3/2
Bulk density, g/cm^3	0.51	0.56	0.73	0.52	0.65
Humus, %	8.5		8.4	8.7	8.3
Bulk N, %	0.250		0.246	0.908	0.908
C : N	19.7		19.8	5.6	5.3
$CaCO_3$, %	27.07		21.14	0	0
Ca^{2+}, mg/100 g	18.0		14.0	16.0	16.0

An automated calculation of the areas between adjacent isolines shown in this figure makes it possible to calculate the mean weighted value of energy expenses on soil formation. It is equal to 1056 MJ/m^2 and varies from 800 to 1500 MJ/m^2. A submeridional gradient of changes in the energy characteristics of soil formation is clearly seen: from 970 MJ/m^2 in the north (Perekop) to 1300 MJ/m^2 in the south. The highest energy potential of pedogenesis is typical of the subtropical southern coast of the Crimea and of western and eastern piedmonts. The lowest energy potential is typical of the Kerch Peninsula and of the northwestern steppe and western foothills.

In the discussion with Ukrainian pedologists [26], it was noted that the chernozems of plain Crimean steppes are close in their properties to the chernozems of moderately continental facies, except for a relatively narrow strip of land with an increased humidity at the northern foothills of the Crimean Mountains, where the properties of the chernozems are close to those in the warm south European facies. On a large-scale soil map [22], the area of foothill chernozems is distinguished to the south of Simferopol. According to the traditional classification, these are calcareous and leached chernozems. On the FAO-UNESCO soil map [28], they are attributed to the group of Luvic Chernozems. In this foothill zone, energy expenses on soil formation reach 1100–1300 MJ/m^2 per year.

The Late Holocene history of the climate, landscapes, and soils of Crimea has been characterized by the generally stable bioclimatic conditions of pedogenesis. The results of spore—pollen analysis [27] indicated that a considerable change in the bioclimatic conditions took place about 3200 years ago, when a drier epoch (4.2–3.5 ka ago) was replaced by a wetter epoch. According to Aleksandrovskii and Aleksandrovskaya [1], four short-term fluctuations of climate and biota can be distinguished in the Late Holocene. In Ukraine, five different climatic stages are distinguished in the past 2800 years [3]; it was shown that three of them were characterized by the decrease in the mean annual temperature by 1.5–2.0°C.

As shown in [12], the periods of the maximum solar activity lasting for 150–250 years and dating back to about 750, 1700, and 1970 years ago were recorded in soils. The analysis of changes in the climate of Europe in the past 1000–1500 years [13] indicated that various indicators of climate changes (historical, hydrological, dendrochronological, and instrumental) display some fluctuations with a definite periodicity of 50–100 years. However, these periods do not correlate with one another, so that it is impossible to establish statistically significant periods of definite climatic fluctuations.

There are no reasons to believe that the climate in the Late Holocene was more stable in comparison with that during the recent period of instrumental measurements. Hence, the amplitudes of climate changes during the five separate stages in the Late Holocene can be judged from the records of weather stations available for a period of more than a century.

It should be noted that the meteorological data used for compiling our map (Fig. 4) were averaged for the period from the second half of the 19th century up to 1980s. Thus, they reflect the average climatic conditions during the period of instrumental measurements. However, these data can also be used to judge the temporal dynamics of climatic characteristics.

According to records at the Genichesk weather station (http://data.giss.nasa.gov), the variation of average annual temperatures in 101 years (since 1884) is from 8.36 to 12.52°C. In the temporal sequence, the coefficient of variation in the average annual temperatures is only 8.2%. The interannual variability in precipitation is more considerable. For Odessa (weather records since 1856), the coefficient of variation reached 26.6%; in absolute values, annual precipitation varied from 192 to 662 mm. It is important that

Table 4. Climatic characteristics of Crimean regions (long-term data)

Weather station	Mean annual temperature, °C	Mean annual precipitation, mm	Humidity factor	Efficient precipitation, mm	Radiation energy input to soil formation, MJ/m^2 per yr
Northwestern region: very dry, moderately hot summer; moderately mild winter					
Armyansk	10.0	341	0.38	263	976
Western steppe region: very dry, moderately hot summer; mild winter					
Chernomorskoe	10.5	316	0.42	247	952
Evpatoria	11.0	358	0.46	283	1062
Plain steppe region: dry, moderately hot summer; moderately mild winter					
Klepinino	10.0	466	0.55	338	1213
Dzhankoi	10.6	491	–	–	1127
Kerch region: very dry, moderately hot summer; mild winter					
Mysovoe	11.0	329	0.44	247	791
Kerch	10.6	412	0.55	301	943
Western piedmont region: very dry, moderately hot summer; very mild winter					
Sevastopol	12.0	395	0.42	292	953
Southwestern piedmont region: moderately dry, warm summer; very mild winter					
Pochtovoe	10.3	554	0.51	209	1151
Eastern piedmont region: moderately dry, warm summer; mild winter					
Simferopol	10.1	576	0.60	420	1195
Yailinskii: wet, moderately cool summer; moderately cold winter					
Ai-Petri	5.7	1052	1.91	1052	961
Southern Slope of the Main Ringe: wet, moderately warm summer; mild winter					
Tentative data [18]	15.4° (VII); –3.6° (I)	960	1.80	–	–
Southern Coast, Mediterranean subtropical climate: droughty and hot summer; moderately warm winter					
Yalta	13.0	635	0.62	558	1380
Alushta	12.3	427	0.46	349	1112
Southeastern: very droughty and hot summer; very mild winter					
Sudak	11.9	318	0.33	238	865
Feodosia	11.7	376	0.40	287	1054

some years with extreme conditions of the soil moistening could greatly affect the character of pedogenesis, including the development of soil humus horizons. The statistical treatment of weather records in Crimea [16] showed that the maximum amount of precipitation in the winter period exceeds the average and minimum amounts by three and seven times, respectively.

Often, the temporal sequences of the heat and moisture supply cannot be synchronized with respect to their impact on the pedogenesis. Thus, wet years may be both colder and hotter than the average and vice versa. In terms of energetics, these parameters can be transformed into integral index of the energy expenses on soil formation (Q) and, thus, to assess temporal changes in this characteristic. For a given weather station, the value of Q upon the mean annual precipitation (precipitation norm) changes from 802 to 860 MJ/m^2 per year due to interannual changes in the air temperature; upon the mean annual temperature (temperature norm), Q values may vary from 378 to 1300 MJ/m^2 due to interannual changes in precipitation. If we analyze Q values for the high and medium annual precipitation and temperature values at a given station, the range of their variation will be comparable with that on the plain territory of the peninsula (from 790 to 1434 MJ/m^2 per year).

It can be supposed that extreme climatic events cannot leave the "long-living" records in the soil properties (i.e., their effects will be erased relatively soon). The main centennial cycles of the water and heat supply described in terms of deviation from the mean values are shown in Fig. 5. The climate changes determined with the use of this approach are realized in the long-term regimes of soil functioning.

If we eliminate "high-frequency" fluctuations, we can see a tendency for a decrease in the mean annual temperature from 1880s to the 1960s with the centennial minimum in 1898–1965. The centennial minimum in the mean annual precipitation was observed from 1927 to 1965; in that period, the mean annual precipitation was by 4 mm lower than in the previous

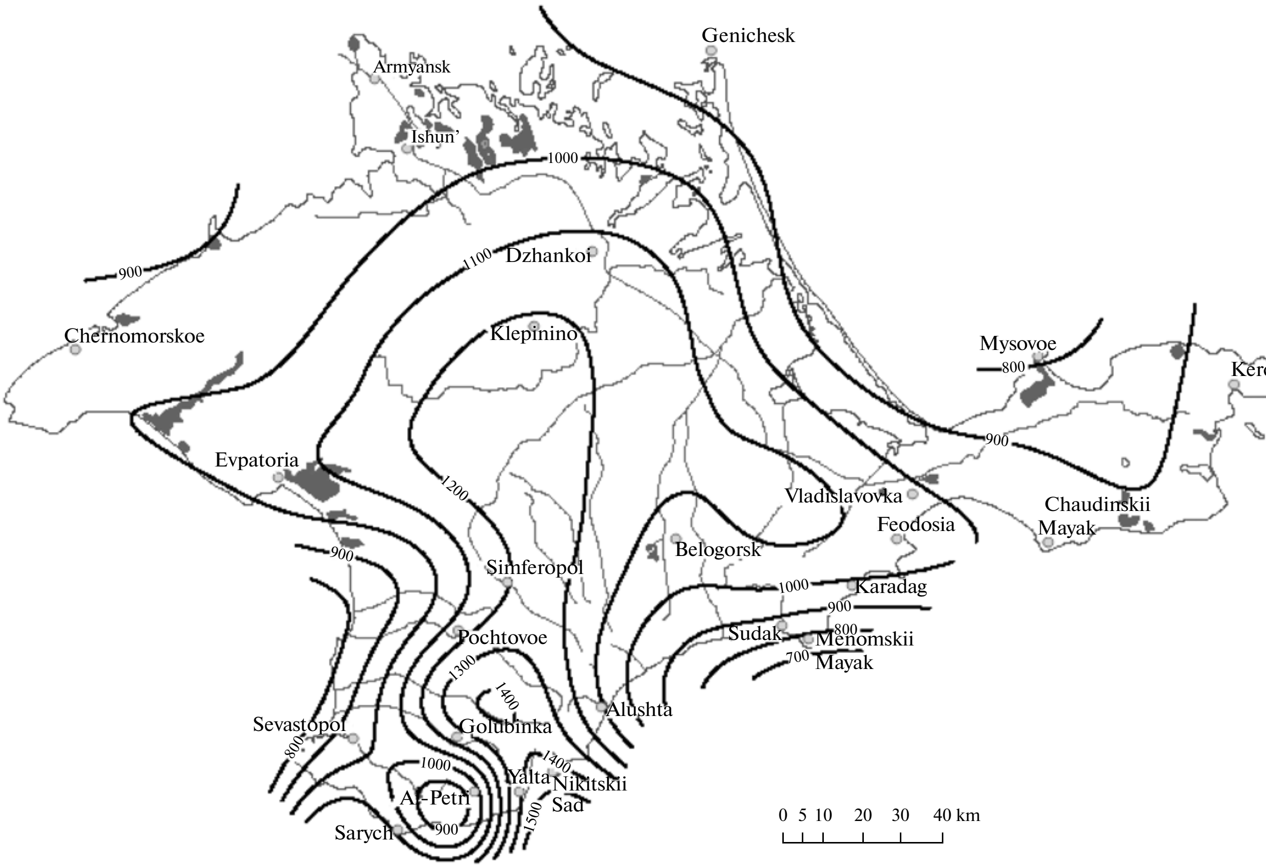

Fig. 4. Distribution of energy expenses on soil formation (Q, MJ/m^2 per yr) within the Crimean Peninsula. The soils with Q equal to 900–1000 MJ/m^2 per yr occupy the largest area (30.29%); the soils with Q 1000–1100 MJ/m^2 per yr, 26.59%; Q 1100–1200 MJ/m^2 per yr, 21.04%; Q 1200–1300 MJ/m^2 per yr, 11.32%; Q 800–900 MJ/m^2 per yr, 7.74%; Q 1300–1400 MJ/m^2 per yr, 2.41%; and Q 1400–1500 MJ/m^2 per yr, 0.44%.

and following years. In the recent decades, the climate changes toward higher temperatures and higher precipitation.

The analysis of changes in the climatic conditions during the past century makes it possible to assume that a similar amplitude of changes has been observed in the entire Late Holocene. Centennial variations in the energy expanses on soil formation are about ±2 MJ/m^2 per year, or less than 1% of the climatic norm for the entire Holocene. This is a relatively low amplitude, which cannot be realized in definite evolutionary changes in the character of soils (Fig. 5).

A question arises: what is the amplitude of climate changes that might be realized in the evolutionary changes in the character of soils? The answer can be obtained on the basis of calculations of the climatic potential of the region. According to Fig. 6, the amplitude of mean annual temperatures within a century of observations reaches 2°C, and the amplitude of the mean annual precipitation reaches 18%. These values are equivalent to changes in the energy expenses (Q) at about 180 MJ/m^2 per year. If such changes have a stable character, the shift in the boundaries between the soil-geographic zones on the plain territory of Crimea may reach 43–52 km. This conclusion is confirmed by the analysis of characteristic distances, at which definite spatial differences in the character of soils are observed. The width of the area of southern chernozems in Crimea is about 20 km, the width of the area of foothill chernozems is about 30–35 km, and the width of the area of dark chestnut soils is about 40 km. Thus, the shifts in the boundaries between these zones by 40–50 km could lead to significant changes in the character of pedogenesis.

The self-development of the soil profile with time is mainly controlled by the soil age. The diversity of analytical data on the properties of the soils of different ages is also conditioned by the differences in the texture and mineralogy of the parent materials and in the intrazonal climatic conditions. If we use an aggregated set of pedochronological data, the climatically conditioned differences will become more pronounced.

To estimate the potential effect of the centennial climatic fluctuations on the growth of soil humus horizons (H), the dependence of the maximum H thickness on energy expenses for pedogenesis can be

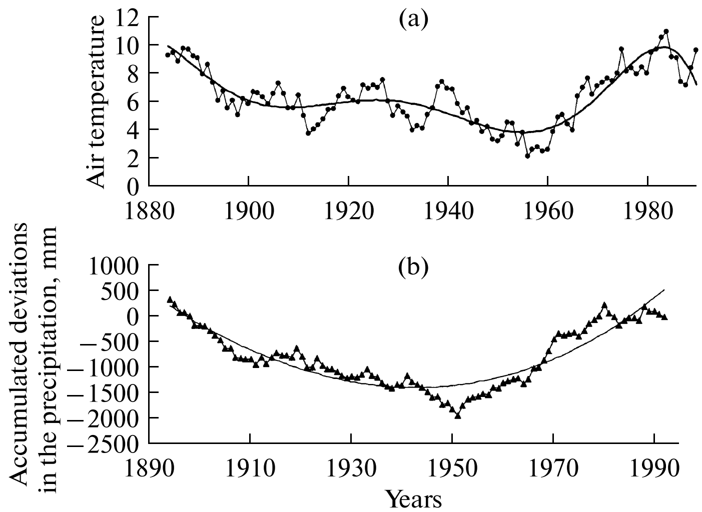

Fig. 5. Integral sums of deviations from the mean annual climatic norms for (a) air temperatures (according to records at the Genichesk weather station) and (b) precipitation (according to records at the Odessa weather station).

applied. The latter dependence was determined from data on a large territory of the East European Plain (N = 215). It can be described by the following equation:

$$H_{\lim} = 10.85 \cdot g \cdot e^{0.0044Q}, \quad (5)$$

where Q is the energy expense for pedogenesis (MJ/m^2 per year), and g is the function reflecting the influence of the texture of parent materials (for the medium loamy soils, $g = 1$).

Taking into account Eq. (1) and (5), we can suggest the following dependence between the climate and the age of soil of a given texture and the thickness of soil humus horizon:

$$H_t = 10.85 \cdot g \cdot e^{0.0044Q}(1 - k \cdot e^{-\lambda t}). \quad (6)$$

In the steppe zone of Crimean plains, the potential rates of the development of soil humus horizon on the medium- and heavy-textured parent materials under the impact of considered variations in energy expenses on soil formation (±180 MJ/m^2 per year) could range from 5.1 to 24.6 mm/100 years. Thus, they could decrease by 2.35 times in the unfavorable epochs and increase by 2 times in the favorable epochs of pedogenesis in comparison with the average climatic conditions typical of the Late Pleistocene.

CONCLUSIONS

The main types of soils of the Crimean Peninsula can be arranged into the following sequence with respect to the rates of the formation of their humus horizons: southern chernozems and dark chestnut soils > mountainous brown forest soils > cinnamonic soils developed from the derivatives of hard rocks. In the newly formed soils of the Late Holocene period, the accumulation of humus proceeded faster than the increase in the thickness of soil humus horizons. Both processes are slowed down considerable at the soil age of 1100–1200 years.

The analysis of the geographic distribution of energy expenses on pedogenesis makes it possible to describe the regularities of soil geography on the basis of instrumental measurements of climatic parameters in the past century. Thus, the meridional change in the character of soils within the plain part of the Crimean Peninsula is conditioned by the increase in the energy expenses on soil formation from 970 to 1300 MJ/m^2 per year. The highest energy potential of pedogenesis is typical of the southern coastal zone with the subtropical climate and the southwestern and eastern pied-

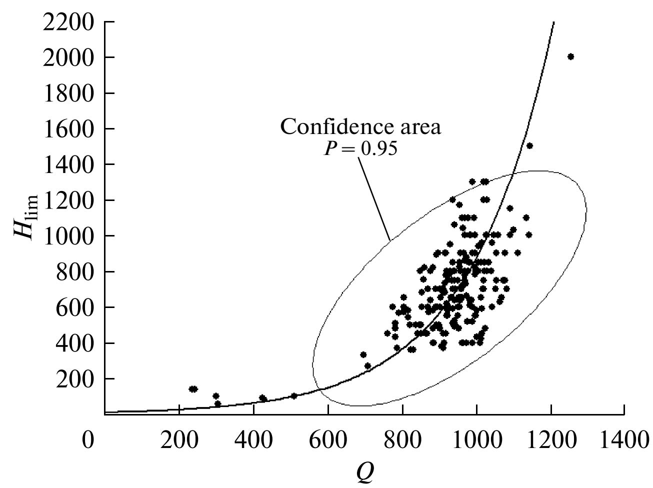

Fig. 6. Dependence of the limiting thickness of the humus horizon ($H_{\lim}$, mm) from the annual radiation energy expenses on soil formation Q, MJ/m^2 per yr.

mont zones; the lowest energy potential is observed in the northwestern steppe region, western piedmont region, and eastern region (the Kerch Peninsula).

The amplitude of centennial variations in energy expenses on pedogenesis under the impact of climatic fluctuations (±180 MJ/m^2 per year) is sufficient to cause shifts in the boundaries between different soil zones and subzones by 43–52 km. The potential rates of the development of soil humus horizons in the steppe part of the Crimea could change under the impact of these fluctuations decreasing by 2.35 times in the unfavorable climatic periods and increasing by 2 times in the favorable climatic periods (in comparison with the average rates calculated for the entire Late Holocene).

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